The Impact of Connected Vehicle Market Penetration and Connectivity Levels on Traffic Safety in Connected Vehicles Transition Period

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Abstract

The recent advent of connected vehicles (CV) technologies could bring unprecedented opportunities to improve road safety, especially under reduced-visibility conditions. Reduced-visibility conditions increase the probability of rear-end crash occurrences and their severity. Moreover, slow traffic may be formed due to bottlenecks on freeways. This phenomenon may lead to higher rear-end crash risk when vehicles approach slow traffic, since drivers might not notice front vehicles' speed reduction in time to respond.

For the abovementioned reasons, this research investigates the CV crash warning systems that have the potential to improve vehicle safety by alerting drivers of imminent situations so they can take timely crash-avoidance action(s). This study provides a driving simulator study to evaluate the effectiveness of the head-up display (HUD) warning system and the audio warning system on drivers' crash-avoidance performance when the lead vehicle makes an emergency stop under fog conditions. Drivers' throttle release time, brake transition time, perception response time, brake reaction time, minimum modified time-to-collision, and maximum brake pedal pressure are analyzed. According to the results, the crash warning system could help decrease drivers' reaction time and reduce the probability of rear-end crashes in a CV environment. In addition, the effects of fog level and driver characteristics, including gender and age, are investigated in this study. The findings of this study could help car manufacturers design rear-end crash warning systems that enhance the effectiveness of the system's application under fog conditions.

Furthermore, this study also aims to develop an integrated variable speed limit (VSL) and CV control strategy to reduce the rear-end crash risk at freeway bottlenecks under fog conditions. Based on the car-following model, the VSL control algorithm is developed considering the different relationships between gap and visibility distance. Then, a feedback control framework is developed to combine the VSL and CV control. The proposed VSL strategy is tested for a freeway section with a bottleneck through VISSIM, and the Intelligent Driver Model (IDM) is employed to build the CV environment. Finally, two measurements, time-to-collision at braking (TTC_{brake}) and total travel time (TTT), are employed to evaluate the effectiveness of the proposed control strategy. The results demonstrate that the VSL control played an important role in reducing the rear-end crash risk. The CV control could also enhance traffic safety by increasing the traffic homogeneity. Moreover, the combination of VSL and CV control (VSL&CV) could further enhance traffic safety and diminish the increase in travel time due to VSL.

1 Introduction

Recently, there has been a clear trend of using connected vehicle (CV) technologies to prevent crashes, especially under adverse weather conditions. Detailed information about nearby vehicles' movement can be provided through vehicle-to-vehicle (V2V) communications, while vehicle-to-infrastructure (V2I) communication can inform drivers about weather conditions, speed limits, crashes, etc. Moreover, it is known that reduced-visibility conditions increase the probability of rear-end crash occurrences and their severity. Previous research pointed out that fog could increase crash severity and multi-vehicle crash risk [1-4]. The reduced-visibility conditions that are caused by fog result in a shorter sight distance and a longer stopping sight distance [3, 5]. On freeways, bottlenecks could occur for various reasons, such as on-ramps, lane closure, special events, and accidents. The bottleneck could reduce the speed and propagate a shockwave to the upstream. Due to the reduced visibility, the drivers from the upstream may not be able to observe the downstream slow traffic and react in time, resulting in increased rear-end crash risk [5] and even severe crashes with multi-vehicle pileups as in recent cases in Florida [6]. Besides CV technologies, another possibility for improving safety under fog conditions is implementing variable speed limits (VSL). The basic idea of VSL control is to provide a proactive intervention by adjusting vehicle speed limits upstream of bottlenecks to prevent rear-end crashes [7, 8]. The VSL control can also enhance traffic safety under inclement weather conditions, such as fog, precipitation, and wind [9].

Above all, we try to investigate drivers' behavior under fog conditions and their response to warning systems, especially under emergency situations. This study also aimed to develop an integrated VSL and CV control strategy to reduce rear-end crash risk at freeway bottlenecks under fog conditions. Therefore, the main research objectives of this project can be summarized as follows:

- Investigating the impacts of CV fog warning systems and verifying whether they could improve traffic safety; and
- Evaluating CV and VSL controls for reducing rear-end crash risk under fog conditions.

Following the brief introduction and overview in Chapter 1, Chapter 2 summarizes literature about CV crash warning systems and VSL control under reduced-visibility conditions. Chapter 3 explains the driving simulator study, Chapter 4 explains the microsimulation study, and Chapter 5 concludes the report and provides suggestions.

2 Literature Review

1. Connected-Vehicle Crash Warning System

Fog is an inclement weather condition with reduced visibility and has a significant impact on driver behavior, traffic flow characteristics, and traffic safety. Compared to crashes under clear conditions, fog-related crashes are prone to be more severe and involve multiple vehicles [10,11]. According to fatal crash statistics from the National Highway Transportation Safety Administration (NHSTA), fog contributed as a major factor to 7,070 fatal crashes that occurred in the United States from 2000 to 2015. In 2008, a fog-related crash with a 70-vehicle pileup happened in Florida, causing five deaths and many injuries [6].

A number of studies have investigated the change in driver behavior under fog conditions. Broughton et al. [12] observed reduced headway distance under fog conditions. It was suggested that drivers may reduce their headway distances to seek visible cues in fog. Based on real-time traffic data and airport weather data, Wu et al. [2] analyzed the traffic flow pattern and found that both volume and speed under fog conditions dropped significantly. By proposing a crash risk increase indicator (CRII), the authors confirmed that crash risks could increase under fog conditions. Mueller and Trick [13] compared experienced and novice drivers' behavioral compensation in fog. The authors suggested that changing speed is the most typical change among all the driving behavioral adjustments corresponding to fog. The study also showed that experienced drivers reduce their speeds more than novice drivers. Wu et al. [3] investigated the impacts of static fog warning systems (beacons and variable message signs) on drivers' speed adjustments for fog conditions using a driving simulator study. The authors found that the warning system could significantly affect drivers' speed adjustments before they drove into the fog area but could not sufficiently change drivers' final speed after entering the fog area.

Since some drivers tend to reduce their headway distance during fog, they may not have enough response time to react to imminent events even if they had reduced their speeds, which results in an increase in the rear-end crash risk [14]. A driving simulator study conducted by Yan et al. [15] further confirmed that drivers' speed compensation in fog conditions could not sufficiently reduce the rear-end crash risk at the medium and high crash risk levels. Meanwhile, although some drivers would keep longer headway distances, rear-end crashes may still happen since they may not be able to see the braking lights of the front vehicle [4].

In recent years, CV crash warning system (CWS) technologies have been gaining increasing acceptance in traffic safety. The technologies provide a vista for enhancing traffic safety under fog conditions, since real-time warning information could be sent to drivers to avoid potential crashes. Previously, CWS technologies were based on radars or cameras. However, bad weather could reduce the systems' accuracy. Connected vehicles could further improve the performance of CWS by deploying V2V or V2I communications [9]. The V2V communications can provide the real-time position and speed of the lead vehicle. Thus, the CWS can detect the sudden slow down or stop of the lead vehicle and alert the driver of the following vehicle with a timely in-vehicle warning message [16]. Many driving simulator studies have been conducted to explore the impact of CWS, studying drivers' response time, throttle release behaviors, brake pedal behaviors, and time to collision (TTC) to evaluate the effectiveness of the warning systems [17-21]. It is worth mentioning that TTC is one of the most prevalent measures used to investigate the safety status in driver simulator studies [22-24]. Moreover, some studies utilized minimum TTC (MTTC) to evaluate drivers' rear-end crash risks during driving simulator experiments [25-27].

In general, warning type is one of the important attributes of a warning system that can significantly affect the effectiveness of warning information [28-29]. Currently, warnings can be categorized into three types: visual CWS, tactile CWS, and audio CWS. The visual CWS usually presents warning messages in an instrument cluster or in a head-up display (HUD) [30]. Lind [31] evaluated the effects of forward collision warning (FCW) and concluded that HUD has the highest detection rate. The audio warning system can be further divided into two types: nonverbal and verbal information. A nonverbal warning system usually provides a repetitive sound, such as a "bi-bi" beep sound, while a verbal warning system delivers information by a synthesized voice that imitates the human voice [32]. The nonverbal warning system is usually utilized to alert drivers to brake under emergency situations, especially during high rear-end-crash-risk situations [33, 34]. Compared to the audio CWS, the visual CWS could help drivers observe risk faster [30]. The tactile CWS can direct drivers' attention to a specific direction or location through the localized vibrations of spatial tactile displays [28]. Compared to tactile CWS, the visual and audio CWS can provide more details about the warning events [35]. Furthermore, the previous studies also demonstrated that multimodal CWS, which integrated visual and audio CWS, could be more effective than visual CWS alone in enhancing drivers' performance.

2. Variable Speed Limits under Reduced-Visibility Conditions

Variable speed limit systems have been widely adopted to reduce crash risk at bottlenecks on freeways [36, 37], and the VSL control strategies developed for traffic safety so far can be generally divided into two categories: reactive rule-based approaches and proactive approaches [38]. For the reactive rule-based approach, real-time VSL decisions are changed based on preselected thresholds of traffic characteristics, such as traffic volume, occupancy, and average speed. The main objectives of these approaches are to harmonize the speed and stabilize the traffic flow. The effects of such approaches have been examined by previous studies [39, 40], and the effectiveness of VSL systems in harmonizing traffic and improving safety has been validated. The limitation of the rule-based strategies is that the strategies were implemented reactively rather than proactively. Hence, the traffic could reach breakdown when the VSL actions are deployed. The proactive approaches monitor the roadway crash risk based on the traffic condition and optimize VSL values to reduce the total crash risk before a real crash occurs. For example, Yu and Abdel-Aty [41] developed a real-time crash risk prediction model and suggested the optimal VSL values to minimize the total crash risk for mountainous freeway. A similar approach was adopted by Wang et al. [42] for freeway weaving segments.

Several studies have found that VSL implementation can improve safety under certain conditions. Field studies have shown that VSL could improve traffic safety by reducing speed differences for vehicles in the same lane or adjacent lanes [43-45]. Abdel-Aty et al. [46] found that implementing VSL control could provide significant improvement for safety under non-congested conditions while crash migration effects may be present. The study by Kang & Chang [45] also demonstrated that VSL control resulted in a decrease in speed variation and an enhancement of traffic safety. However, the results for VSL effects on mobility are mixed. Lee et al. [47] concluded that VSL could reduce crash potential, but it could also lead to higher travel time. On the other hand, some studies found that VSL systems could reduce travel time through work zones [48-50]. Meanwhile, drivers' compliance levels were also found to have impacts on the effects of speed limits [51-53]. Hellinga and Mandelzys [52] conducted a microscopic simulation analysis to evaluate the relationship between drivers' compliance and traffic safety. This study concluded that traffic safety could be improved by a higher compliance rate, while traffic efficiency may decrease. In addition to the abovementioned safety impact, other studies attempted to resolve traffic breakdown or improve throughput by optimizing VSL strategies [43, 54]. By preventing too many vehicles from entering bottlenecks, VSL could mitigate freeway capacity drop and prevent the ensuing traffic breakdown [54, 55].

Currently, various VSL strategies have been also implemented under inclement weather conditions. However, in most of the strategies, pre-set fixed values of speed limit were used based on practical experiences. For example, a field trial of VSL was carried out in the Netherlands, and the VSL system included both a clear weather algorithm and a rain algorithm [56]. During rainy conditions, the posted speed limit would decrease from 120 km/h to 100 km/h or 80 km/h depending on rain intensity. Li et al. [9] proposed a VSL strategy to reduce secondary crash risk during inclement conditions. The proposed strategy was based on car-following models, and the results were confirmed by microscopic simulation. Although the algorithm evaluated the impact of reducing visibility on rear-end crash risk, detailed kinematic relationships during reduced-visibility conditions were not considered. Wu et al. [3] proposed a new algorithm to evaluate the rear-end collision risk under conditions considering reduced visibility. Based on the relationship between gap and visibility distance, the car-following maneuver is divided into different situations and a corresponding algorithm to determine rear-end crash risk was proposed for each situation.

Recently, there has been considerable interest in using CV technologies to prevent potential crash. Detailed information about nearby vehicles' movements could be provided through V2V communications, while V2I communication could inform drivers about weather conditions, speed limits, crashes, etc. Previous research suggested that V2V systems could reduce 79% of crashes and that combined V2V & V2I systems could reduce 81% of crashes, excluding crashes related to drivers with physiological impairment [57]. Microsimulation experiments could be utilized to analyze the impact of CVJeong et al. [58] reported CV and inter-vehicle communication potential in reducing rear-end conflicts by up to 85% with market penetration of 100%. Our previous driving simulator study [4] also suggested that a driver could be well prepared for an emergent event occurring ahead with the warning messages in the CV environment. Talebpour and Mahmassani [59] employed the Intelligent Driver Model (IDM) to simulate the CV environment and found that CV could improve string stability and enhance traffic safety. The effects of VSL strategies could also be improved by CV technologies. Khondaker and Kattan [38] evaluated the performance of VSL in a CV environment. They concluded that deploying VSL signs under CV conditions could benefit both traffic safety and mobility. Meanwhile, CV-based VSL strategies were found to have positive effects on mitigating traffic congestion [60]. Moreover, the study conducted by Li et al. [8] suggested that the combination of cooperative adaptive cruise control (CACC) and VSL control could mitigate the negative effects of the mixed traffic flow of the manual driving vehicles and the CACC vehicles. However, to the best of our knowledge, the effects of combining the VSL and CV controls have not been investigated under fog conditions.

3 Driving Simulator Study

3. Driving Simulator Experiment

3.1.1 Participants

Fifty-four participants were recruited for this study. The average age of the participants was 38.4 years old, ranging from 18 to 75 years old. Each participant held a valid driver license and had at least 1 year of driving experience. The experiment lasted about 30 min for each participant. Institutional Review Board (IRB) approval was obtained before starting the experiments.

3.1.2 Apparatus

The National Advanced Driving Simulator (NADS) MiniSim was used for this experiment. The NADS MiniSim provided a 130 degree horizontal by 24 degree vertical field of view in front of the seated participants with three screens (22.5 inches high and 40.1 inches wide each). Two speakers were installed in the front to mimic the sound of the passenger car as well as deliver the audio warning messages, and a third speaker was mounted below the driver's seat to simulate roadway vibrations. The text warning messages were presented through a HUD interface at the bottom of the middle screen (Figure 3.1), which was set up to be transparent and would not obstruct the participants' view. The simulator was equipped with a four-channel video capture system and collected driving data at a rate of 60 Hz.

Figure 3.1 - NADS MiniSim driving simulator with HUD interface

3.1.3 Scenario Designs

The experiment was designed as a 3 x 2 x 3 mixed factorial design with warning types (No Warning, HUD Only, HUD & Audio) as a within-subject variable and age (young: 18-24 years old, working age: 25-54 years old, old: 55-75 years old) and fog level (moderate and dense) as between-subject variables. Our previous study suggested that fog could have significant effects on drivers' behaviors when the visibility distance is less than 300 ft [3]. Hence, the visibility distance of 300 ft (see Figure 3.2(a)) was selected as the moderate fog condition. Also, it was suggested that drivers could have very high crash risk in fog conditions when the visibility is very low since they would not have enough time to respond to an emergency event [61]. Hence, a visibility distance of 100 ft. (see Figure 3.2(b)) was selected as the dense fog condition to test the effects of warning system under hazardous conditions. Meanwhile, it was found that drivers' behaviors may vary among different age groups [62-65]. Hence, the age group was considered a between-subject variable and was used for the recruitment of participants in this study. A total of 54 participants were recruited in this study. Each fog level had 27 participants with 9 participants in each age group, and each participant performed the experiment under three warning conditions: No Warning, HUD Only, and HUD & Audio.

(a) Moderate fog **(b) Dense fog**

Figure 3.2 - Fog levels

The participants resumed driving on the outer lane of a two-lane straight roadway segment under clear conditions. A lead vehicle was placed in front of the test vehicle with a speed of 50 mph (73.33 ft/s). The 50 mph speed was the drivers' average speed under fog conditions observed in the authors' previous driving simulator study [3]. The drivers were asked to drive from the clear conditions to the fog conditions and not overtake the lead vehicle. Drivers followed the lead vehicle for about 1 mile in the fog so that they could get familiar with the fog environment and adapt their driving behavior accordingly. Then, a risky scenario was introduced in order to test the participants' performance under the hazardous condition: the lead vehicle was triggered to make an emergency stop with a high deceleration rate of 16 ft/s^2 (4.88 m/s^2).

With the reduced visibility, it might have been difficult for drivers to observe the braking light of the lead vehicle. However, the lead vehicle could deliver a warning message if under the CV environment. After receiving the warning message, the vehicle could warn the driver immediately. In the experiment, we mimicked the CV warning function in the driving simulator. A trigger was added in the simulator to deliver the warning message based on the headway distance between the test vehicle and the lead vehicle after the lead vehicle started to decelerate. To provide an effective warning message, the headway distance for delivering the warning message was carefully determined. The drivers' reaction time and deceleration rate were set to be 1.5 s and 11.15 ft/s^2 (3.40 m/s^2), respectively [66]. When the participants received the warning message, as suggested by Wu et al. [4], the lead vehicle could have three different statuses: (1) starting to decelerate; (2) decelerating; and (3) stopping. For the three different statuses, the minimum stopping distance for the test vehicle ranged from 110 ft. to 351 ft.; the detailed calculation process is provided by Wu et al. [4]. Hence, in this study, the warning message was delivered when the headway distance between two vehicles was less than 400 ft. Also, such a design could ensure that the participants would receive the warning message before they saw the brake light of the lead vehicle. Two types of warning strategies ("HUD Only" and "HUD & Audio") were explored to compare with the no-warning conditions. Once the warning system was triggered, the HUD Only warning would display the words of "Slow Vehicle Ahead" for about 1 s. The HUD & Audio warning delivered a beep sound along with the HUD message. It should be noted that the purpose of the study was to investigate the effects of a real-time CV rear-end crash-avoidance warning system under fog conditions; the technological requirements to realize such a system in the real world are beyond the scope of this study.

3.1.4 Procedure

Upon arriving at the laboratory, each participant was briefly introduced to the requirements of the experiment, and all participants were required to read and sign a consent form. Participants were notified that they could quit the experiment at any time in case of motion sickness. Before the formal experiments, the participants had at least 10 minutes to be trained and to familiarize themselves with the operation of the driving simulator. Then, they performed the formal driving experiments under either moderate or dense fog with three different warning conditions in a random sequence. It should be noted that the gender of participants was also carefully considered when assigning the fog levels. Between each trial, participants were given at least 5 minutes to rest. After the experiment, the participants were required to complete a survey about their experience with the scenarios. More than 90% of the participants thought the driving simulator had a high level of realism and the HUD was helpful, while only 60% of the participants thought the audio warning sound was helpful.

3.1.5 Dependent Variables

Figure 3.3 shows a typical example of the curves of vehicles' speeds and the sequence of events when the participants encountered a lead vehicle that was braking. Based on the key time moment shown in the figure, several critical measurements were defined and extracted to evaluate the participants' driving performance. These measurements are explained as follows.

(1) Throttle Release Time

Time to initial throttle release ($t_{initial}$): the time between the onset of the lead vehicle's braking and the moment when the participant begins to release the throttle pedal.

Time to final throttle release ($\mathrm{t_{Release}}$): the time between the moment when the participant begins to release the throttle pedal and the moment at which the participant completely releases the throttle pedal.

Time to initial brake ($\mathrm{t_{brake}}$): the time between the moment when the participant completely releases the throttle pedal and the moment at which the participant begins to press the brake pedal.

(1) Brake Transition Time

Time to 25% brake ($t_{25\%brake}$): the time between the moment of the initiation of pressure on the brake pedal and the moment when the test vehicle pedal pressure reached 25% of the maximum pedal force that each participant would apply. The maximum brake pedal force limit of the test vehicle was 180 lbf.

Time to 50% brake ($\mathrm{t_{50\%brake}}$): the time between the moment of the initiation of pressure on the brake pedal and the moment when the test vehicle pedal pressure reached 50% of the maximum pedal force that each participant would apply.

Time to 75% brake ($\mathrm{t_{75\%brake}}$): the time between the moment of the initiation of pressure on the brake pedal and the moment when the test vehicle pedal pressure reached 75% of the maximum pedal force that each participant would apply.

Time to maximum brake ($\mathrm{t_{maxbrake}}$): the time between the moment of the initiation of pressure on the brake pedal and the moment when the test vehicle pedal pressure reached the maximum brake pedal force.

(2) Response Time

Perception response time (PRT): the time between the moment when the participant notices the braking of the lead vehicle and the moment when the participant starts to brake. When the headway distance is shorter than the visibility distance, the driver can be alerted to the braking of the lead vehicle by seeing its brake lights. Otherwise, the driver will be notified of the braking of the lead vehicle when the warning information is provided.

Brake Reaction Time (BRT): the time between the lead vehicle brake onset and the time when the participant begins to brake.

It should be noted that the BRT is different than the PRT. The reaction time includes the PRT and the time from the moment when the lead vehicle starts to brake to the moment at which the driver realizes the lead vehicle's is braking (see Figure 3.2(a)). The PRT is utilized to describe how quickly the participant responds after receiving stimulation, while the BRT is used to describe how quickly the participant responds after a risky situation is present.

(3) Minimum Modified Time-to-Collision

Minimum modified time-to-collision (MMTTC): the time it would take for the test vehicle to hit the lead vehicle given their current speeds and acceleration/deceleration. Traditionally, only the speeds were considered to calculate the TTC, which leads to the assumption that a collision will happen only if the speed of the following vehicle is greater than that of the lead vehicle [67]. Such an assumption would ignore a lot of potential conflicts due to acceleration or deceleration discrepancies [68]. Hence, this study utilizes the modified TTC considering both the speeds and the acceleration/deceleration as suggested in previous studies [68, 69]. The modified TTC can be calculated based on the trajectory projection of two consecutive vehicles, given their relative distance, speed, and acceleration information:

$$V_F t + \frac{1}{2} a_F t^2 \geq D + V_L t + \frac{1}{2} a_l t^2 \tag{1}$$

$$\frac{1}{2} \Delta a t^2 + \Delta V t - D \geq 0 \tag{2}$$

where

V_F: Following vehicle's speed (ft/s);

V_L: Lead vehicle's speed (ft/s);

a_F: Following vehicle's acceleration (ft/s^2);

a_L: Lead vehicle's acceleration (ft/s^2);

ΔV: Relative speed (ft/s), $\Delta V = V_F - V_L$;

Δa: Relative acceleration (ft/s^2), $\Delta a = a_F - a_L$;

D: Initial relative distance (ft);

t: Time (s).

By solving the two equations, the modified TTC for the rear-end conflict can be calculated. For the detailed calculation process, please refer to the previous studies [68, 69]. The minimum value is selected from the time interval between the moment when the lead vehicle starts to brake and the time when the driver brakes to stop behind the lead vehicle.

(4) Maximum Brake Pedal Pressure

Maximum brake pedal pressure ($Brake_{max}$): the maximum value of brake pedal pressure observed during the braking event, which should be less than or equal to 180 lbf.

4. Experiment Results

Although 54 participants were recruited in the experiment, the data of only 48 participants were collected for the analysis since 6 older participants (4 older females and 2 older males) could not finish the experiment due to motion sickness. In the completed 144 trials ((54-6) ×3), seven trials were excluded because some participants chose the steering wheel to maneuver around the lead vehicle instead of braking to avoid hitting the lead vehicle and some participants drove too slowly and were not able to follow the lead vehicle. Hence, a dataset containing information for 137 (144-7) trials was created for the analysis.

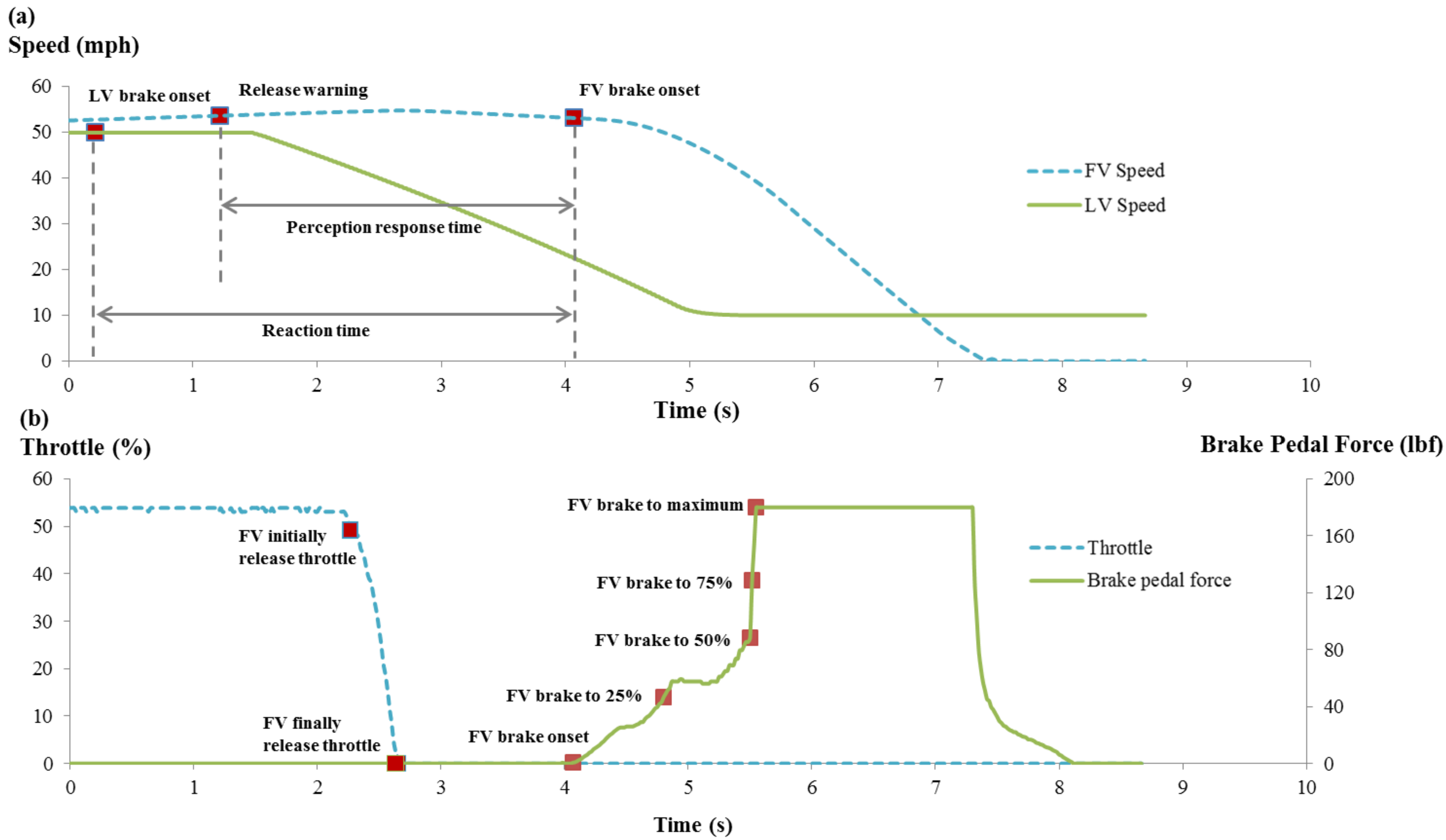


Figure 3.3 - Rear-end crash-avoidance behavior.

Note: LV indicates the lead vehicle; FV indicates the following vehicle.

Prior to the statistics test, all data except the variable MMTTC and potential conflict were subjected to the Kolmogorov-Smirnov test, which indicated that all the data were normally distributed. For the measurements of the participants' rear-end crash-avoidance behavior, the repeated measures multivariate analyses of variance (MANOVA) was conducted for throttle release time measurements and brake transition time measurements, in which high correlations were expected. MANOVA is a type of multivariate analysis that can be utilized to conduct data analysis for the data with more than one dependent variable. MANOVA control the over inflation of Type 1 error [70-72]. Repeated measures analyses of variance (ANOVA) were then conducted on the significant factors revealed by the MANOVA analysis. For the significant factors with more than two groups, a set of post hoc analyses was conducted to further compare the difference. For the other measurements, including response time, $\mathrm{Brake}_{\mathrm{max}}$, only repeated measure ANOVA and post hoc analyses were performed. In addition, the Friedman test was used for MMTTC since the variable was not normally distributed. The statistical significance level was set to be alpha=0.1.

3.1.6 Throttle Release Time

Three measurements were employed to assess the participants' throttle release time: time to initial throttle release ($t_{initial}$), time to final throttle release ($t_{Release}$), and time to initial brake (t_{brake}). The repeated measures MANOVA analysis suggested that only the warning type (F=6.18, p=0.003) had significant effect on drivers' throttle release time. However, no significant effect of different fog levels, age groups, and genders could be observed in terms of the throttle release time.

The ANOVA results indicated that the time to initial throttle release (F=5.97, p<0.01) and the time to final throttle release (F=4.09, p=0.02) contributed to the multivariate effects. Post hoc tests, shown in Table 3-1, suggested that participants under the No Warning condition needed more time to start and finish the throttle release maneuver. Since drivers could be alerted to the hazard event earlier under the warning system, they could take earlier actions to avoid the potential collisions. However, there was no significant difference between the HUD Only warning and the HUD & Audio warning, which indicated that adding an audio warning system would not significantly affect participants' awareness of impending accidents and hence would not shorten the throttle release time.

Table 3-1 Post hoc test of the effects of warning type for $t_{initial}$ and $t_{Release}$

Paired Condition	Dependent Variables	
	Time to initial throttle release	Time to final throttle release
No Warning vs HUD Only	1.08**	0.35**
No Warning vs HUD & Audio	1.44**	0.36**
HUD Only vs HUD & Audio	0.36	0.01

** indicates significant at an alpha level of 0.05, * indicates significant at an alpha level of 0.1

3.1.7 Brake Time

Participants' brake transition times were examined by four measurements: time to 25% brake ($t_{25\%brake}$), time to 50% brake ($t_{50\%brake}$), time to 75% brake ($t_{75\%brake}$), and time to maximum brake ($t_{maxbrake}$). The MANOVA test revealed significant effects of warning type (F=3.06, p=0.05) and age (F=2.69, p=0.07). However, there was no significant difference between male and female participants (F=0.02, p=0.89) or between moderate and dense fog conditions (F=0.02, p=0.89) in terms of brake transition time.

The subsequent repeated measures ANOVA analysis showed that warning type has significant main effect on both $t_{75\%brake}$ (F= 2.66, p=0.07) and $t_{maxbrake}$ (F=2.79, p=0.06). As shown in Table 3-2, the post hoc test indicated that the time to 75% brake and maximum brake became shorter under the No Warning condition than under the HUD & Audio condition. No significant difference could be observed between the two warning types. Since drivers could brake earlier under the warning system, they had more time to decelerate and should have been less likely to make an emergency brake.

In addition, the ANOVA test results of age illustrated significant impact on $t_{75\%brake}$ (F= 2.45, p=0.09) and $t_{maxbrake}$ (F=5.96, p<0.01). The post hoc test suggested that young drivers tended to take longer to reach 75% and maximum pedal force compared with working age and older drivers. Since young drivers have less driving experience, they made more aggressive crash-avoidance behaviors when the dangerous condition presented. However, no significant difference was found between working age and older drivers.

Table 3-2 Post hoc test of the effects of warning types and age for $t_{75\%brake}$ and $t_{maxbrake}$

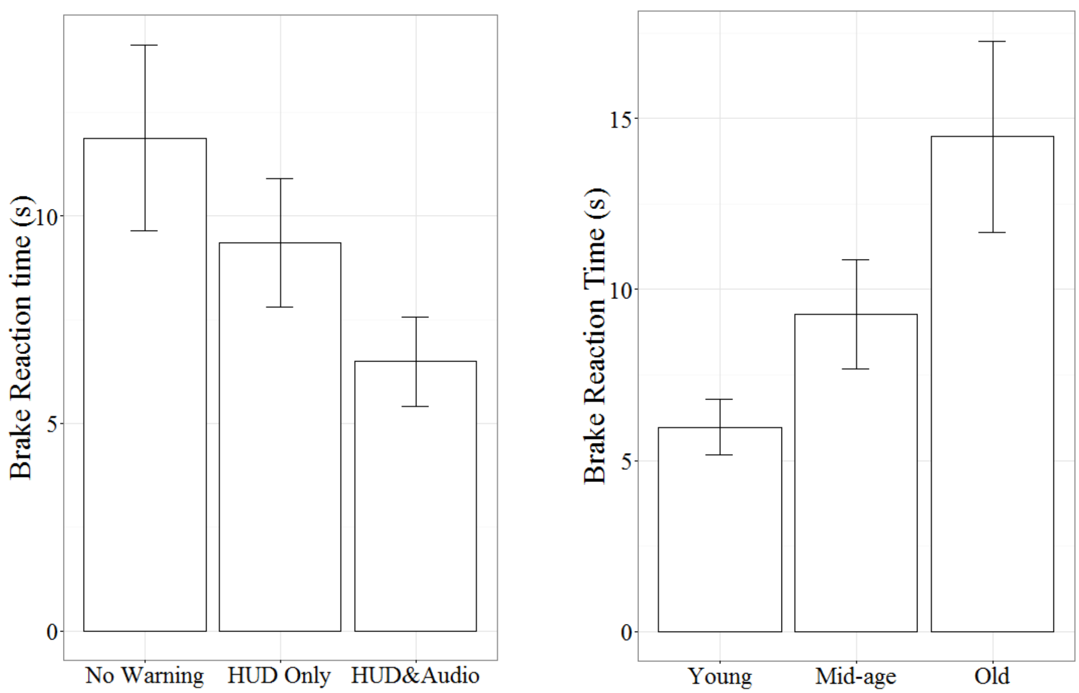
Paired Condition		Dependent variables	
		Time to 75% brake	Time to maximum brake
Warning type	No Warning vs HUD Only	-0.30*	-0.28*
	No Warning vs HUD&Audio	-0.35*	-0.49*
	HUD Only vs HUD&Audio	-0.05	-0.21
Age	Young vs Working Age	0.28*	0.44*
	Young vs Older	0.32*	0.73**
	Working Age vs Older	0.03	-0.21

** indicates significant at an alpha level of 0.05, * indicates significant at an alpha level of 0.1

3.1.8 Response Time

The repeated measures ANOVA revealed that warning type, fog level, gender, and age did not have significant impact on the PRT. Participants, on average, reported a perception response time of 2.21 s, a result similar to those of previous studies [73, 18].

The influences of warning type, fog level, gender, and age on BRT were examined through similar repeated measures ANOVA tests. The effects of warning type (F=3.56, p=0.03) and age (F=3.68, p=0.03) were significant. However, fog level (F=2.11, p=0.15) and gender (F=0.83, p=0.37) did not have significant impact on the BRT. Figure 3.3 presents the mean BRT for the different warning types and age groups, as well as the post hoc test results for the two significant factors. There was a significant difference in BRT between the No Warning condition and the HUD & Audio condition. Compared with the No Warning condition, the HUD & Audio condition had a smaller BRT (see Figure 3.4(a)). It is also useful to note that no significant difference could be observed between the HUD Only condition and the other two conditions. Regarding the effect of age, the BRT was the largest in the older age group, which indicated that older drivers need more time to respond to an emergency event (see Figure 3.4(b)). However, the difference between young drivers and working age drivers was not significant.



Post hoc test

Comparison Groups	Difference
No Warning vs HUD Only	2.52
No Warning vs HUD & Audio	5.38*
HUD Only vs HUD & Audio	2.86

Post hoc test

Comparison Groups	Difference
Young vs Working age	-2.33
Young vs Old	-7.92**
Mid-age vs Old	-5.59*

(a) Warning type

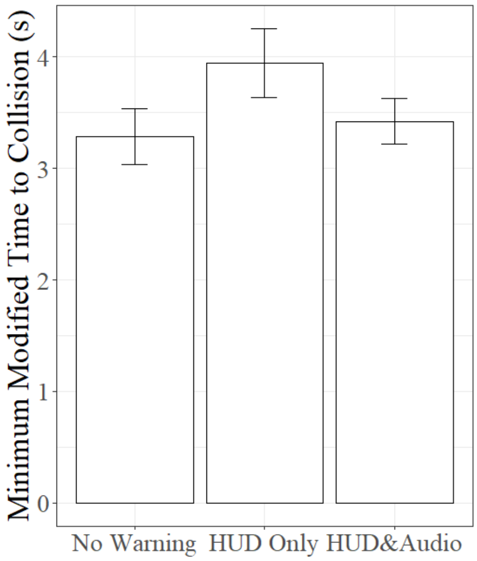
(b) Age

** indicates significant at an alpha level of 0.05, * indicates significant at an alpha level of 0.1

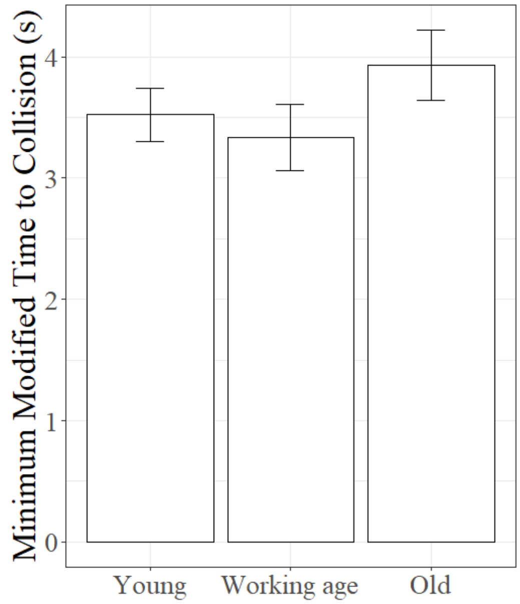
Figure 3.4 - Mean brake reaction time under different warning types and age groups

3.1.9 Minimum Modified Time to Collision

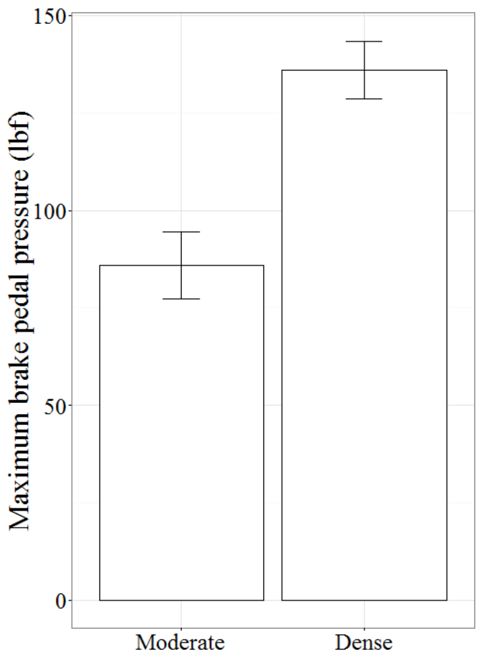
The MMTTC is an essential surrogate measure to evaluate rear-end crash risk under fog conditions. The Friedman test results suggested that the effects of warning type (χ^2=29.57, p<0.01) and fog level (χ^2=13.09, p<0.01) on MTTC were significant while the effects of gender (F=0.13, p=0.72) and age (F=0.07, p=0.93) were not. The mean MMTTCs of the different warning types and age groups are presented in Figures 3.5(a) and 3-5(b).



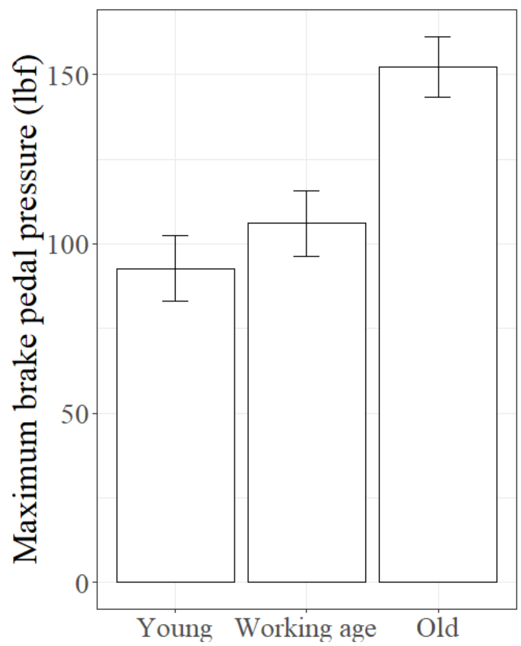
(a) Warning type for MMTTC



(b) Fog level for MMTTC



(c) Fog level for $Brake_{max}$



(d) Age for $Brake_{max}$

Figure 3.5 - Minimum time to collision under different warning types and fog levels.

The post hoc analysis indicated that the MMTTC under the No Warning condition (M=3.29 s, S.D.=1.68 s) was significantly lower than that under the HUD Only condition (M=3.94 s, S.D.=2.05 s) (see Figure 3.4(a)). Although the No Warning condition also had lower MMTTC compared with HUD & Audio condition, the difference was not significant, presumably owing to the random effect. With the warning system, drivers were better prepared to avoid the potential conflict. Meanwhile, no significant difference could be observed between the two warning types.

Figure 3.4(b) suggests that older drivers (M=3.93 s, S.D.=1.60 s) could have significantly larger MMTTC than working age drivers (M=3.34 s, S.D.=1.94 s). Although the difference between older drivers and young drivers is not significant, young drivers (M=3.52 s, S.D.=1.59 s) tended to have smaller MMTC than older drivers.

3.1.10 Maximum Brake Pedal Pressure

The ANOVA analyses revealed significant effects of fog level (F=13.01, p<0.01) and age (F=6.12, p<0.01) on the maximum brake pedal pressure. However, warning type (F=1.42, p=0.25) and gender (F=0.13, p=0.72) did not significantly affect the maximum brake pedal pressure. The result of warning type indicated that the warning message would not affect participants' employment of the maximum brake pedal pressure if the participants had realized the risky situations through either seeing the brake lights of the lead vehicle or noticing the warning message. The mean maximum brake pedal pressures for different fog levels and different age groups are illustrated in Figures 3.4(c) and 3.4(d).

Figure 3.4(c) indicates that drivers would employ a larger brake pedal pressure under dense fog conditions (M=136.04 lbf, S.D.=61.46 lbf) than under moderate fog conditions (M=86.81 lbf, S.D.=69.62 lbf).

As for the effects of age, older drivers (M=152.19 lbf, S.D.=50.01 lbf) tended to have larger maximum brake pedal pressure than those in the other two age groups, and there was no significant difference in the brake pedal pressure between young drivers (M=92.72 lbf, S.D.=69.22 lbf) and working age drivers (M=106.01 lbf, S.D.=71.88 lbf) (see Figure 3.4(d)).

5. <u>Result Discussions</u>

This study investigated the effectiveness of a CV CWS on participants' performance during the process of rear-end crash avoidance under fog conditions. Scenarios were specifically designed for rear-end crashes caused by the emergency stop of the lead vehicle. These experiments were designed to test different warning types along with different fog levels and participants' age and gender groups. Table 3-3 summarizes the effects of the tested factors on the participants' rear-end crash-avoidance behavior. Participants' throttle release time ($t_{Release}$, t_{brake}) is only affected by the warning type while participants' brake transition time ($t_{75\%brake}$, $t_{\max brake}$) could be affected by both warning type and age. As for the two types of response time, BRT could be affected by warning type and participants' age while no factor has significant effects on PRT. In addition, MTTC is affected by the warning type and fog level, while $Brake_{max}$ could be affected by fog level and age.

Table 3-3 Summary of effects of factors

Factors		Warning Type	Fog Level	Age
Throttle Release Time	$t_{initial}$			
	$t_{Release}$	**		
	t_{brake}	**		
Brake Transition Time	$t_{25\%brake}$			
	$t_{50\%brake}$			
	$t_{75\%brake}$	*		*
	$t_{\mathrm{max}brake}$	*		**
Response Time	PRT			
	BRT	**		**
Minimum Modified Time to Collision	$MMTTC$	**		**
Maximum Brake Pedal Pressure	$Brake_{max}$		**	**

Note: ** indicates significant at an alpha level of 0.05, * indicates significant at an alpha level of 0.1

3.1.11 Effects of Crash Warning System

Previous studies suggested that drivers could make better decisions if they prepared for the subsequent road conditions [74]. Whether drivers could successfully avoid rear-end crashes depended on how quickly the drivers could identify the impending crashes and execute crash-avoidance actions. In this study, both shorter throttle release time and shorter BRT could be found with the presence of warning systems, which indicates the advantage of the warning systems. Meanwhile, drivers' braking process could be smoother (smaller $t_{75\%brake}$and $t_{\mathrm{max}brake}$) with the warning systems. In addition, drivers could have greater MMTTCs with warning systems, which confirmed the benefits of CWS under fog conditions.

Although previous studies showed that a warning message could lower drivers' PRT and increase the maximum braking pedal pressure [75], no significant difference was identified in the PRT and maximum braking pedal pressure. In this study, both the start moment of the warning message and the moment when the participant saw the brake lights of the lead vehicle could be regarded as stimulus, and the response to the stimuli of each driver under the emergency situation was relatively similar [28]. Hence, drivers would have similar PRT and similar maximum braking pressure. Meanwhile, previous studies suggested that multimodal CWS (e.g., visual and audio warning) could further improve drivers' rear-end crash-avoidance performance [35]. However, no significant difference was identified in the participants' throttle release time, brake transition time, or other performance measurements between the HUD Only CWS and the HUD & Audio CWS in this study. This phenomenon could be due to the fact that drivers are prone to be more careful when driving under fog conditions [76, 15, 3, 4], and the auditory warning has been found to have safety benefits when drivers are distracted [34, 77, 30,,42].

3.1.12 Effects of Fog Level

Car-following driving behavior in fog is a complex task since participants need to consider the interactions between their speeds and the lead vehicles' speeds. Previous studies have confirmed that participants tend to adopt safer driving maneuvers, such as reducing speed and being less distracted, under fog conditions to avoid potential crashes arising from the reduced visibility [9]. In this study, no significant effect of fog level was observed for the participants' throttle release time, brake transition time, and response time; participants did press the brake pedal harder in dense fog. However, a larger maximum brake pedal pressure was found under dense fog conditions, which indicated that the drivers had to select a larger deceleration rate to avoid hitting the lead vehicle. When the fog became dense, participants in the test vehicle could not see the brake lights of the lead vehicle, resulting in higher rear-end crash risk [78].

3.1.13 Effects of Age and Gender

There was no significant difference between different age groups in the PRT. However, older participants had significantly longer brake reaction times because they need more time to make mental calculations [79]. Also, it should be noted that working age drivers also needed a longer brake reaction time than young drivers, although the difference was not significant. In addition, young participants took longer to reach 75% and maximum brake forces, which means their braking processes might be smoother than those of other participants [80]. Meanwhile, since older drivers started braking relatively late and they were more sensitive to the potential risk [81, 82], they could have smaller TTC values by braking harder.

Although some of the previous studies found that male drivers were more likely to engage in risky driving behavior [83], no significant gender effect was found in this study, which is in line with other previous fog-related driving behavior studies [13, 15]. Thus, it can be reasoned that, when driving in fog, males' risky driving behavior might be counteracted by speed or other compensation behavior in fog.

4 Microsimulation Study

6. Methodology

4.1.1 Variable Speed Limit Strategy

In previous studies, many VSL strategies have been proposed for different purposes, such as improving traffic efficiency and enhancing traffic safety. It was found that VSL could reduce crash risks by decreasing the speed variations of different roadway segments [36, 84]. In this study, the VSL strategy was developed based on our previous study [3], which considered the occurrence conditions of rear-end crashes in fog. For two consecutive vehicles, if the front vehicle decreases its speed due to congestion, rear-end crashes may happen when the following vehicle keeps small headway or responds late. Meanwhile, since fog reduces the sight distance, drivers may not be able to recognize the reduced speed ahead and respond in time, which may lead to higher crash risk during fog [3].

Assuming that two consecutive vehicles approach the downstream bottleneck, the lead vehicle *n* starts to decelerate from a higher speed v_2 to a lower speed v_1 at time t_1. As discussed in our previous study [3], there could be two general situations when the lead vehicle begins to decelerate based on the different relationships between the gap between the two vehicles (*G*) and the sight distance (*S*): (1) $\mathrm{G} < \mathrm{S}$; (2) $\mathrm{G} \geq \mathrm{S}$.

Situation 1: $G < S$

Figure 4.1 illustrates the situation when the gap between the two vehicles *G* is smaller than the sight distance *S*, which means the following vehicle *n+1* could see the brake lights of the lead vehicle immediately when the lead vehicle *n* starts to decelerate. After a reaction time t_r, the following vehicle begins to brake from speed v_2 to speed v_1 to avoid a collision with the lead vehicle. Then, a rear-end crash could occur if:

$$d_n + d_n^1 + G < d_{n+1}^2 + d_{n+1} \tag{1}$$

where d_n represents the deceleration distance of lead vehicle *n*; d_n^1 represents the traveling distance of lead vehicle *n* with the speed v_1; d_{n+1}^2 indicates the traveling distance of following vehicle *n+1* with the speed v_2 in reaction time t_r; and d_{n+1} is the deceleration distance of following vehicle *n+1*. Assuming that the desired vehicle deceleration rate is a, Equation (1) can be written as:

$$\frac{v_2^2 - v_1^2}{2a} + v_1 t_r + G < v_2 t_r + \frac{v_2^2 - v_1^2}{2a} \tag{2}$$

Then, we could have:

$$v_2 > v_1 + \frac{G}{t_r} \tag{3}$$

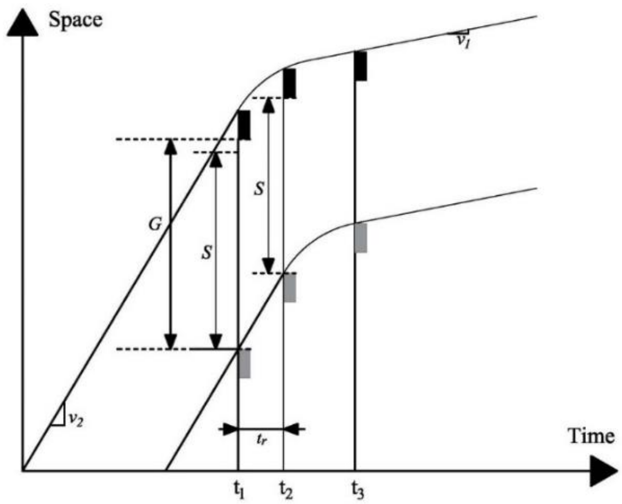


Figure 4.1 - Trajectories of two vehicles under Situation 1

Equation (3) can be aggregated using the microwave radar data [9]:

$$v_2 = \frac{1}{N}\sum_{n=1}^{N} v_2 = \overline{V_U}[t+\Delta t] \tag{4}$$

$$v_1 = \frac{1}{N}\sum_{n=1}^{N} v_1 = \overline{V_D}[t+\Delta t] \tag{5}$$

$$\begin{aligned} G &= \frac{1}{N}\sum_{n=1}^{N} G_n = \frac{1}{N}\sum_{n=1}^{N}(H_n - L_n) \\ &= \frac{1}{N}(\sum_{n=1}^{N} H_n - \sum_{n=1}^{N} L_n) = \frac{1}{N}(\sum_{n=1}^{N}\frac{1}{\bar{K}_u[t+\Delta t]} - N\bar{L}) \\ &= \frac{1}{N}(\sum_{n=1}^{N}\frac{1}{\bar{O}_u[t+\Delta t]} - N\bar{L}) = \frac{\bar{L}}{\bar{O}_u[t+\Delta t]} - \bar{L} \\ &= \bar{L}(\frac{1-\bar{O}_u[t+\Delta t]}{\bar{O}_u[t+\Delta t]}) \end{aligned} \tag{6}$$

where Δt is microwave radars' updating period; $\overline{V_U}[t+\Delta t]$ and $\overline{V_D}[t+\Delta t]$ are the average speeds at the upstream and downstream detectors, respectively, during $[t, t+\Delta t]$; H_n represents the distance headway between vehicle *n* and *n+1*; L_n denotes the length of vehicle *n*; $\bar{K}_u[t+\Delta t]$ is the average density at the upstream detector location during $[t, t+\Delta t]$; $\bar{O}_u[t+\Delta t]$ is average occupancy at the upstream detector during $[t, t+\Delta t]$; and $\bar{L}$ is average vehicle length.

With Equations (4)-(6), Equation (3) can be expressed as:

$$\overline{V_U}[t, t+\Delta t] > \overline{V_D}[\, t+\Delta t] + \frac{\bar{L}}{t_r}(\frac{1-\bar{O}_u[t+\Delta t]}{\bar{O}_u[t+\Delta t]}) \tag{7}$$

Accordingly, the optimal speed to avoid the occurrence of rear-end collision can be calculated by:

$$V_{opt}[x_i, t+\Delta t] = V[x_{i-1}, t] + \frac{\bar{L}}{t_r}(\frac{1-O[x_i, t]}{O[x_i, t]}) \tag{8}$$

where $V[x_{i-1}, t]$ is the speed reported from the microwave radar station at location x_{i-1} at time t (see Figure 4.2); $O[x_i, t]$ denotes the occupancy reported from the microwave radar station at location x_i at time t; t_r is the reaction time (1.5 s, which was used in previous studies) [85-87].

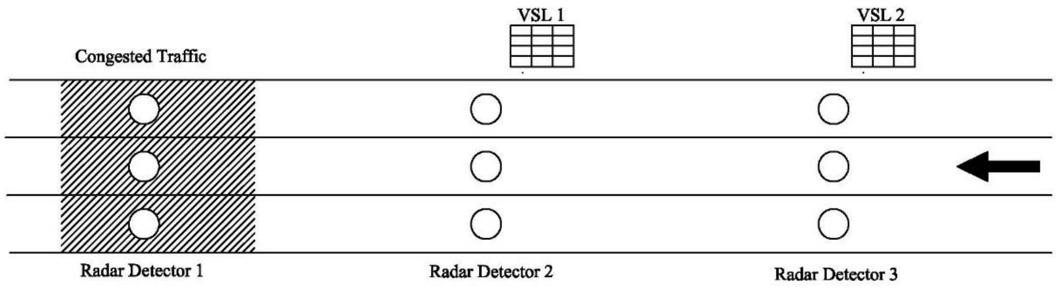
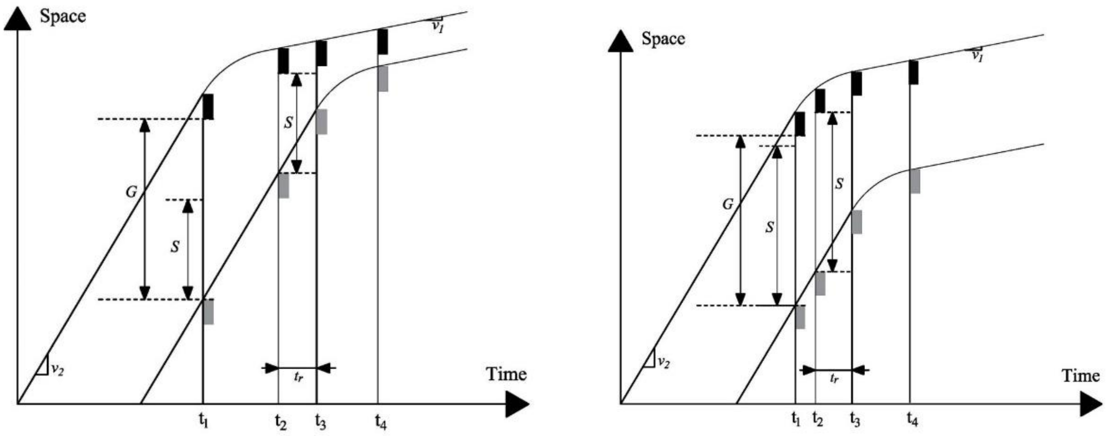


Figure 4.2 - An illustration of roadway section with VSL system

Situation 2: $\boldsymbol{G \geq S}$

Figure 4.3 shows the time-space diagram of vehicle trajectories under Situation 2. When the lead vehicle n starts to decelerate at time t_1, the following vehicle n+1 will maintain speed v_2 as the driver of the following vehicle cannot see the brake lights of the lead vehicle. The following vehicle will not react to the lead vehicle's deceleration maneuver until t_2 when the following vehicle's driver can see the lead vehicle, i.e., the gap between the two vehicles becomes equal to the sight distance S. As shown in Figure 4.3, there are two possible speed statuses for the lead vehicle at time t_2: (1) the lead vehicle has reduced its speed to v_1; (2) the lead vehicle is still decelerating, but its speed is still larger than v_1. The relations between the gap and sight distance for the two statuses should be $G > \frac{(v_2-v_1)^2}{2a} + S$ and $S \leq G \leq \frac{(v_2-v_1)^2}{2a} + S$, respectively. The detailed discussion and computation of the relations can be found in our previous study [3].



(1) Status 1 **(2) Status 2**

Figure 4.3 - Trajectories of two vehicles under Situation 2

For Status 1, as shown in Figure 4.3, the driver of the following vehicle could see the lead vehicle at time t_2. After a reaction time t_r, the following vehicle starts to decelerate and reduce its speed to v_1 at time t_4. From t_2 to t_4, a rear-end crash could occur if:

$$v_1(t_r + \frac{v_2 - v_1}{a}) + \mathrm{S} < v_2 t_r + \frac{v_2^2 - v_1^2}{2a} \tag{9}$$

Hence, we could have:

$$v_2 > v_1 + (2aS + a^2 {t_r}^2)^{1/2} - a t_r \tag{10}$$

With Equations (4) - (6), Equation (10) can be expressed as:

$$\overline{V_U}[t, t + \Delta t] > \overline{V_D}[t, t + \Delta t] + (2aS + a^2 {t_r}^2)^{1/2} - a t_r \tag{11}$$

Then, the corresponding optimal speed to avoid the potential rear-end crash can be calculated as:

$$V_{opt}[x_i, t + \Delta t] = V[x_{i-1}, t] + (2aS + a^2 {t_r}^2)^{1/2} - a t_r \tag{12}$$

In our study, a equals 2.8 m/s^2, which has been commonly used [88].

For Status 2, let the time between time t_1 and t_2 be Δt, which means Δt = $t_2 - t_1$. Since the driver of the following vehicle could see the lead vehicle at time t_2, we could have:

$$v_2 \Delta t - \frac{1}{2} a \Delta t^2 + G = v_2 \Delta t + S \tag{13}$$

By solving Equation (13), Δt could be calculated by:

$$\Delta t = \sqrt{\frac{2(G - S)}{a}} \tag{14}$$

Hence, the speed of the lead vehicle $v_2{}'$ could be calculated by:

$$v_2{}' = v_2 - a\Delta t = v_2 - \sqrt{2a(G-S)} \tag{15}$$

During the time from t_1 to t_4, the time t_{v1} that the lead vehicle travels at speed v_1 can be computed as:

$$t_{v1} = t_r + \frac{v_2 - v_1}{a} - \frac{v_2' - v_1}{a} \tag{16}$$

Then, a read-end crash might occur if:

$$\frac{v_2^2 - v_1^2}{2a} + v_1\left(t_r + \frac{v_2 - v_1}{a} - \frac{v_2' - v_1}{a}\right) + G < v_2(\Delta t + t_r) + \frac{v_2^2 - v_1^2}{2a} \tag{17}$$

By solving Equations (15) and (17), we could have:

$$v_2 > v_1 + \frac{G}{\sqrt{\frac{2(G-S)}{a}} + t_r} \tag{18}$$

With Equations (4) - (6), Equation (18) could be expressed as:

$$\overline{V_U}[t+\Delta t] > \overline{V_D}[t+\Delta t] + \bar{L}\left(\frac{1-\bar{O}_u[t+\Delta t]}{\bar{O}_u[t+\Delta t]}\right)\frac{1}{\sqrt{2\left(\bar{L}\left(\frac{1-\bar{O}_u[t+\Delta t]}{\bar{O}_u[t+\Delta t]}\right) - S\right)/a} + t_r} \tag{19}$$

Then, the corresponding optimal speed to avoid the potential rear-end crash can be calculated as:

$$V_{opt}[x_i, t+\Delta t] = V[x_{i-1}, t] + \bar{L}\left(\frac{1-O[x_i,t]}{O[x_i,t]}\right)\frac{1}{\sqrt{2\left(\bar{L}\left(\frac{1-O[x_i,t]}{O[x_i,t]}\right) - S\right)/a} + t_r} \tag{20}$$

In summary, the optimal speed of avoiding the occurrence of rear-end collision under different situations could be calculated by:

$$V_{opt}[x_i, t+\Delta t] = \begin{cases} V[x_{i-1},t] + \frac{\bar{L}}{t_r}\left(\frac{1-O[x_i,t]}{O[x_i,t]}\right), & if\ \bar{L}\left(\frac{1-O[x_i,t]}{O[x_i,t]}\right) \le S \\ V[x_{i-1},t] + (2aS + a^2 t_r{}^2)^{\frac{1}{2}} - at_r, & if\ \bar{L}\left(\frac{1-O[x_i,t]}{O[x_i,t]}\right) > \frac{(V_{SL}[x_i,t] - V[x_{i-1},t])^2}{2a} + . \\ V[x_{i-1},t] + \bar{L}\left(\frac{1-O[x_i,t]}{O[x_i,t]}\right)\frac{1}{\sqrt{\frac{2\left(\bar{L}\left(\frac{1-O[x_i,t]}{O[x_i,t]}\right) - S\right)}{a}} + t_r}, & otherwise \end{cases} \tag{21}$$

In this study, the real-time traffic data was obtained from radar detectors, while weather data such as visibility distance was collected from weather sensors.

In addition, the effects of drivers' compliance levels on the effectiveness of the VSL control were tested in this study. The compliance rate could be modeled in VISSIM as a function of the posted speed limit in which higher compliance rates were related to higher posted speed limits while lower compliance rates were related to lower speed limits [89]. The posted speed limit of VSL ($VSL(t + \Delta t)$) will be adjusted based on the relationship between speed of real-time traffic ($V_D(t)$) and the posted speed limit at time t ($VSL(t)$). Hence, we could have:

$$VSL(x_i, t + \Delta t) = (1 + \alpha) * \mathrm{V_{opt}}(x_i, t + \Delta t) \tag{22}$$

$$\alpha = \frac{V[x_i, t] - VSL(x_i, t)}{VSL(x_i, t)} \tag{23}$$

where $VSL(x_i, t + \Delta t)$ is the optimal speed limit for location x_i at time $t + \Delta t$ based on Equation (21); $VSL(x_i, t + \Delta t)$ is the displayed speed limit for location x_i at time $t + \Delta t$; α is the real-time traffic compliance level indicator, which is calculated by Equation (23); $V[x_i, t]$ represents the detected speed at location x_i at time t; and $VSL(x_i, t)$ is the displayed speed limit for location x_i at time t. As suggested by the previous study [38], the use of the real-time compliance could help provide a more robust and efficient VSL control strategy.

In addition, to avoid sudden changes in traffic operation, constraints are set up with the consideration of traffic operation and safety [90]:

(1) Spatial constraint: the maximum difference between the posted speeds of two neighboring detectors is 10 mph;
(2) Temporal constraint: the maximum difference between the posted speeds of two consecutive time steps is 10 mph.

4.1.2 *Connected Vehicle*

With the development of V2V technologies, drivers are able to communicate with nearby vehicles because the vehicles can send/receive information to/from other vehicles. With V2V communication, drivers can know the driving environment, road condition, and weather condition downstream of their current locations. Hence, a deterministic acceleration modeling framework is suitable for this environment [91, 59]. Recently, IDM has been applied to model the CV environment, since it has been proven to provide greater realism and reflect the operation of driving-assistant systems [38, 88, 92, 93, 59]. Hence, the IDM model was used in this study. It is a non-linear car-following model that specifies a following vehicle's acceleration as a continuous function of the vehicle's current speed, the ratio of the current spacing to the desired spacing, and the difference between the lead and following vehicles' velocities. The function for the acceleration a_{IDM} is as follows [94]:

$$a_{IDM}(t + t_a) = max\left\{b_m, a_m[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*}{s}\right)^2]\right\} \tag{24}$$

$$s^* = \mathrm{s}_0 + max\left\{0, v\mathrm{T} + \frac{\mathrm{v}\Delta\mathrm{v}}{2\sqrt{a_m b}}\right\} \tag{25}$$

where t_a is the reaction time, b_m represents the maximum deceleration rate, a_m is the maximum acceleration rate, v_0 is the desired speed; v is the following vehicle's speed; v_0 is the desired speed, δ is the acceleration exponent, s is the gap between consecutive vehicles, s_0 is the minimum gap at standstill, T is the safe time headway, and b is the desired deceleration.

4.1.3 Feedback Control System

Figure 4.4 displays a feedback control system to integrate the VSL and CV controls. On freeways, a bottleneck can occur for various reasons, including construction, crashes, spillover of off-ramp, etc. Then, the bottleneck could reduce the speed and propagate a shockwave to the upstream. As the downstream speed gets reduced, the vehicles from the upstream might cause rear-end crashes if they approach the congested segment at high speeds. The rear-end crash risk could be even higher under fog conditions, since drivers from the upstream might not recognize the dangerous conditions because of reduced visibility.

The proposed control algorithm of integrating the VSL and CV control strategies could mitigate the rear-end crash risk under this situation in fog. The traffic data (speed and occupancy) collected at location x_{i-1}, the posted speed limit at location x_i, and the visibility distance are used to calculate the safe speed for upstream vehicles approaching the congested segments. The real speed limit will be posted at Location x_{i-1} accordingly, if the real speed limit is less than the initial speed limit (70 mph). All VSL are determined spatially from downstream congested segments to the upstream. In this study, it is assumed that the visibility distance is the same in the microsimulation environment.

The CV control could help to overcome the limitations of VSL-only control that some drivers would not notice the change of speed limits under fog conditions. Besides, the CV technologies could mitigate the adverse impact of fog by providing the following vehicle the location information of the lead vehicle. The VSL information could be sent to all CVs through V2I communication. As suggested by the previous studies, the CVs would follow the suggested safe speed homogeneously [385]. Hence, it is expected that the CV technology could help provide more effective VSL control strategies to reduce rear-end crash risks in fog. On the other hand, the VSL control strategies could provide a safer driving environment for CVs under the fog condition.

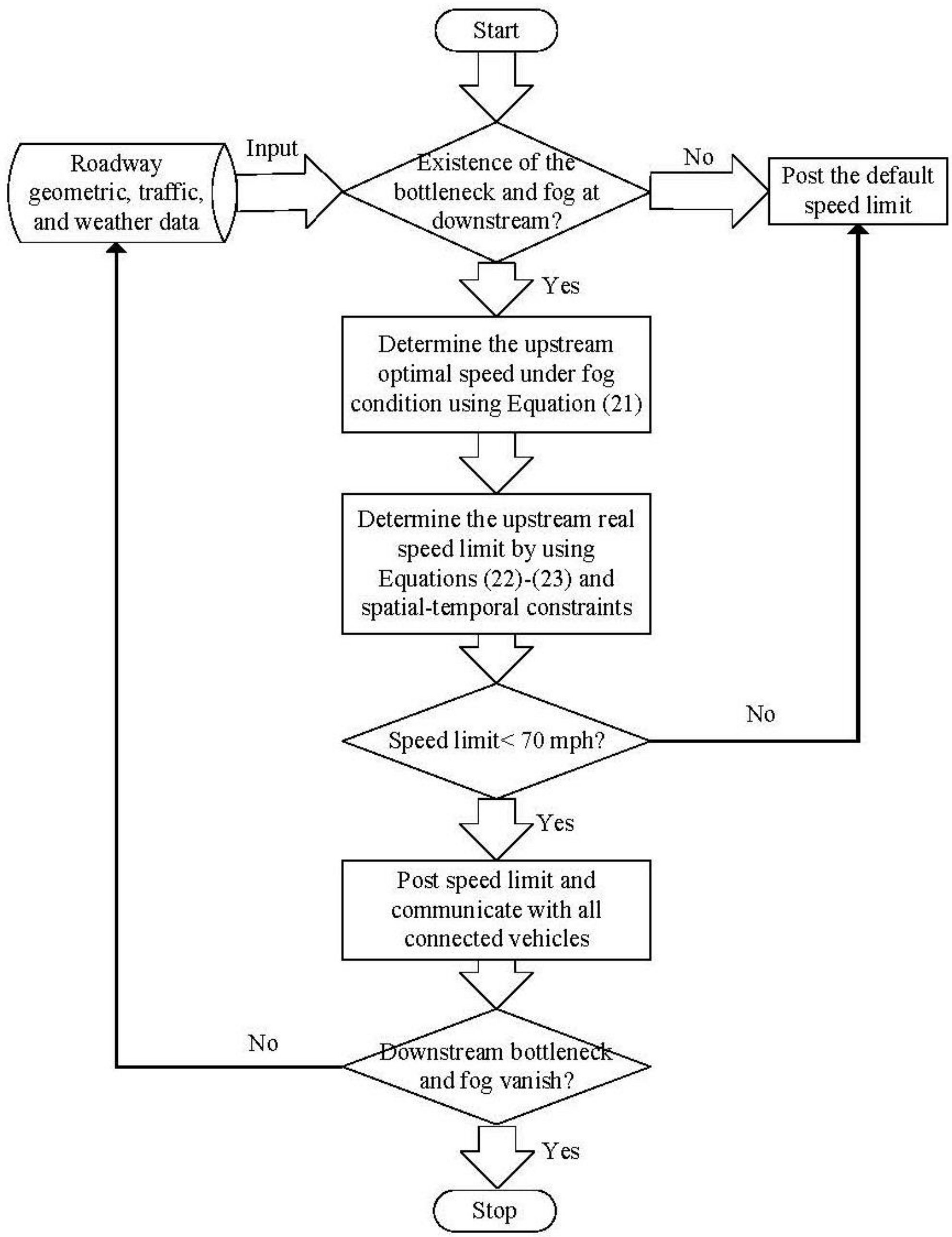


Figure 4.4 - Flowchart of the VSL and CV control algorithm

4.1.4 Evaluation Measurements

To evaluate the proposed VSL and CV control strategy, an appropriate surrogate safety measure should be applied to evaluate the rear-end crash risks. The surrogate measures describe the relationship between collision risk and traffic data. Previous studies have suggested different measures such as speed standard deviation, TTC, post-encroachment time (PET), and deceleration rate to avoid the crash (DRAC) [9, 95, 41]. Among these measurements, the TTC has been commonly used to evaluate the rear-end crash risk [9, 96]. The TTC indicates the time required for two consecutive vehicles to collide if they keep their present speed when the following vehicle moves faster than the lead vehicle:

$$\mathrm{TTC} = \begin{cases} \dfrac{G}{v_f - v_l}, & if\ v_f > v_l \\ \infty, & if\ v_f \leq v_l \end{cases} \tag{26}$$

where v_f is the speed of the following vehicle and v_l is the speed of the lead vehicle. Nevertheless, one of the major concerns of fog-related rear-end crashes is that the following vehicles may not be able to respond in time when the front vehicle has a sudden stop because of the reduced visibility [3]. During the simulation, traffic data was collected at six detectors in the VISSIM network, and few small TTCs between vehicles were observed during the simulation. Hence, the regular TTC might not be appropriate to assess the rear-end crash risk under the fog condition. To appropriately evaluate the rear-end crash risk in fog, Peng et al. [96] suggested using TTC at braking (TTC_{brake}), which describes situations when the lead vehicle stops suddenly. The TTC at braking also considers the reduced visibility in fog, i.e., the visibility distance was used to replace the actual gap when the visibility distance was less than gap. In this study, the gap will always be used regardless of the visibility distance if two consecutive vehicles are both CVs since the following vehicle could have the gap information. Hence, with the consideration of CV, the TTC at braking can be calculated as follows:

$$TTC_{brake} = \begin{cases} \dfrac{G}{v_f}, & \text{If both the lead vehicle and the following vehicle are connected vehicle} \\ \dfrac{\min(S, G)}{v_f}, & \textit{otherwise} \end{cases} \tag{27}$$

According to the definition of TTC at braking, there could be numerous TTC values at each simulation time step due to many simulated vehicles. Hence, the dangerous TTC_{brake} percentage is calculated to evaluate the rear-end crash risk at each simulation stamp. The TTC_{brake} percentage can be expressed as follows.

$$TTC_{brake\%} = \frac{\text{Number of TTC} < \text{Threshold TTC}}{Total\ number\ of\ recorded\ TTC} \tag{28}$$

In previous studies, the threshold of TTC varies from 1 to 3 s [9, 8]. In this study, the threshold of TTC was set to be 2 s.

Previous research found that VSL may increase travel time, since relatively smaller speed limits are applied. In order to evaluate the effects of VSL and CV on traffic efficiency, the total travel time (TTT) is calculated as follows:

$$TTT = \sum_{i=1}^{N} T_i \tag{29}$$

where T_i is the travel time of vehicle *i*, and N is the total number of vehicles during the simulation.

7. Microsimulation Experiment Design

The simulation experiments were conducted to test the abovementioned integrated VSL and CV control strategies with a freeway section in Florida (westbound of I-4) where severe fog-related crashes have happened [97]. The feasibility of utilizing the VSL and CV control strategies to proactively improve traffic safety for a bottleneck area on the freeway in fog were investigated. The studied area starts at Mile Post 7.999 and ends at Mile Post 17.308 with three lanes in each direction and a speed limit of 70 mph. Figure 4.5 shows the layout of the studied roadway segment. There are six detectors virtually implemented on the roadway. A typical freeway bottleneck caused by a severe crash was selected for the simulation. The crash occurred between Detectors #1 and #2, and two lanes were blocked due to the crash. The traffic flow data were collected from the microwave vehicle detection system (MVDS), and the corresponding weather data was collected from a fog monitoring system (FMS) installed at the roadside [98]. The FMS could provide weather data including air temperature, surface moisture, rainfall, and visibility distance [3]. At the upstream of the crash location, three VSLs were implemented at Detectors #3, #4, and #6.

Figure 4.5 - The simulation roadway with the bottleneck

The in-field traffic data under heavy fog conditions, from 6:15 a.m. to 8:15 a.m. on February 2, 2016, with a visibility distance between 45 m and 88 m, was collected for the model calibration to represent traffic conditions during fog. After excluding 30 minutes of VISSIM warm-up time and 30 minutes of cool-down time, 60 minutes of VISSIM data were used for the calibration and validation. The simulation network was calibrated by traffic volume at 15-min intervals and was validated by average speeds at 15-min intervals. Geoffrey E. Heavers (GEH) statistics were calculated by traffic volume from both in-field detectors and simulation at 15-min intervals.

$$GEH = \sqrt{\frac{(E-V)^2}{(E+V)/2}} \tag{30}$$

where E is the simulated volume (vehicles/hour), and V is the field volume (vehicles/hour). If more than 85% of the measurement locations' GEH values are less than 5, then the simulated flow would accurately reflect the field traffic flow [43, 90]. The average speeds from the field and simulation were used. The absolute speed difference between the simulated speeds and the field speeds should be within 5 mph for more than 85% of the checkpoints [99]. The results of the ten simulation runs with different random seeds showed that 91.25% of the GEH values were less than 5, and 92.50% of the aggregated speeds in the simulation were within 5 mph of the field speeds. The validation results demonstrated that the calibrated network can accurately represent the field roadway traffic flow characteristics.

To better reflect the fog conditions, the VISSIM network was revalidated with respect to both traffic operation and safety. The headway was selected to validate the calibrated VISSIM network by using a two-sample t-test. The result suggested that the mean simulated headway was significantly different from the mean field headway, which indicated that the simulation network requires further calibration to reflect the fog condition. In this study, the drivers' behavior parameters under fog conditions were calibrated by conducting a sensitivity analysis based on in-field data. The ten car-following parameters (CC0 to CC9) were tried, and each set was run ten times with different random seeds. The ten parameters are CC0 (average standstill distance), CC1 (desired time headway), CC2 (variation in the following distance), CC3 (threshold for entering the following mode), CC4 and CC5 (sensitivity parameters), CC6 and CC7 (parameters for the oscillation of vehicular speeds during following), CC8 (standstill acceleration), CC9 (acceleration at a specific speed) [89]. For each parameter, a range of values (9 values), which includes the default, was determined based on previous studies and engineering judgment. A total of 730 simulation runs [(1 base-models + 9x8 car-following parameters) times 10 random seeds] were conducted [100]. The sensitivity analysis results showed that three parameters are vital to reflect the fog condition: CC0 (standstill distance), CC1 (headway time), and CC2 (following variation). According to the results of sensitivity analysis, the safety distance parameters (i.e., CC0, CC1, and CC2) would decrease compared to the default values in the fog condition. The default values of CC0, CC1, and CC2 in VISSIM were 4.92 ft, 0.9 s, and 13.12 ft, whereas the calibrated value were found to be 3.28 ft, 0.7 s and, 9.84 ft, respectively. For further validation, headway was again used to validate the new calibrated VISSIM network using a two-sample t-test. After replicating the fog condition, the simulated mean headway had a distribution identical to that of the field mean headway, which suggested that the simulation network was well calibrated and validated with respect to both traffic and safety under the fog condition.

The scenario considering vehicles without any control technique was first simulated as a reference. Then, the scenarios with the VSL and CV control strategies were developed in the simulation. The VSL algorithm was fulfilled by the Component Object Model (COM) interface, which is used to program and regulate vehicle movements. Meanwhile, the CV behavior was regulated by the external driver behavior model in VISSIM, and it was based on IDM and developed with a C++ program [43]. The values of the parameters in the IDM model were determined based on previous studies [94, 5 88, 92, 101). The parameters of the CV behavior model are presented in Table 4-1.

Table 4-1 IDM model parameter settings

Model Parameters	Value
Reaction time, t_a	1.5 s
Maximum deceleration rate, b_m	2.8 m/s^2(9.2 feet/s^2)
Maximum acceleration rate, a_m	1 m/s^2 (3.3 feet/s^2)
Desired speed, v_0	120 km/h (75 mile/h)
Acceleration exponent, δ	4
Minimum gap at standstill, s_0	2 m (6.6 feet)
Safe time headway, *T*	0.6 s
Desired deceleration, *b*	2 m/s^2 (6.6 feet/s^2)

The main objective of this study was to evaluate the proposed VSL strategy and understand the impacts of the VSL strategy together with CV technologies on traffic safety. Thus, in order simplify the experiment, only a 0% CV penetration rate and a 100% CV penetration rate were tested in this study. Three variables were considered: traffic volume (low and high), penetration rates of CV (0% and 100%), and VSL compliance rates (0%, 30%, 60, and 100%). The scenarios with VSL compliance rates of 0% meant that no VSL control strategy was implemented. As suggested by previous studies [9], the CV could help to overcome the limitations of VSL-only control in that drivers would respond differently to the proposed speed. Hence, the compliance rate of VSL should be 100% if the CV penetration rate is 100%. In total, 12 scenarios were included during the experiment (Table 4-2), and the scenarios can be divided into four types: base (no VSL or CV), VSL only, CV only, and VSL under CV environment (VSL&CV). The values of high volume were set to be triple the values of low volume, which is based on the field traffic data. Ten runs were carried out with different random seed values for each scenario. Each simulation lasted 2 hours, with the first 30 minutes as the warm-up period.

Table 4-2 Simulation scenarios

Scenario number	Volume	VSL Compliance rate	CV Penetration rate
1	Low	0%	0%
2	Low	0%	100%
3	Low	30%	0%
4	Low	60%	0%
5	Low	100%	0%
6	Low	100%	100%

7	High	0%	0%
8	High	0%	100%
9	High	30%	0%
10	High	60%	0%
11	High	100%	0%
12	High	100%	100%

8. Microsimulation Results and Discussion

4.1.5 Effects of Variable Speed Limit (VSL Only)

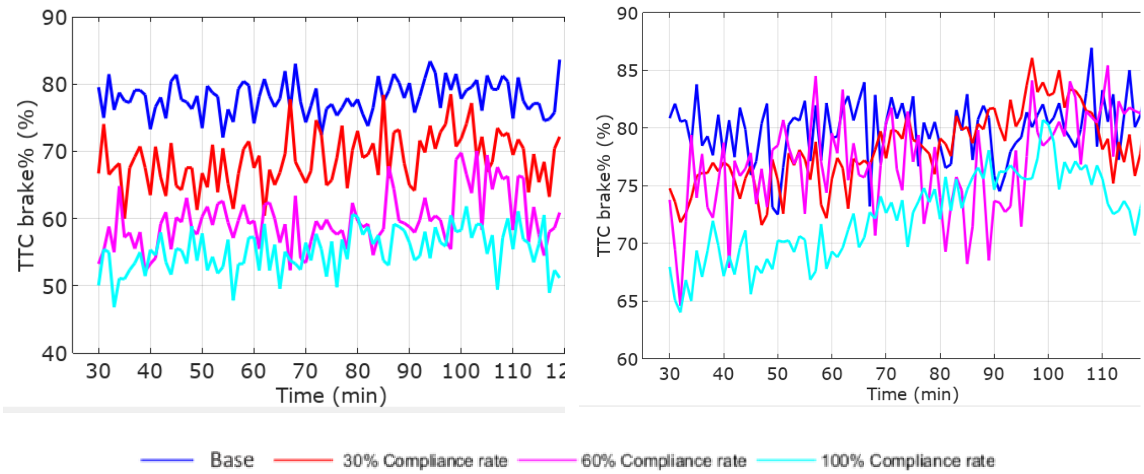
The vehicles without any control strategy were first simulated as a reference. Table 4-3 summarizes the effects of VSL control with various driver compliance rates compared with the base condition (without any control). Hence, Scenarios 1, 3, 4, 5, 7, 9, 10, and 11 were used for the analysis in this subsection. Three different compliance rates (30%, 60%, and 100%) were tested in the simulation for two different traffic conditions (i.e., low volume and high volume). As shown in Table 4-3, the VSL control could efficiently reduce the rear-end crash risk, and the reduction in $TTC_{brake\%}$ based on all detectors varies across the different VSL compliance rates. To specify, the crash risks decreased with the increase of VSL compliance rates. When the compliance rate reached 100%, the VSL control achieved the largest reductions of 29.5% and 6.3%, respectively, for the scenarios of low and high volumes. The difference in crash risks under three different compliance rates confirmed the conclusion that VSL's impacts on safety varies by drivers' compliance levels [52]. Compared with the high-volume scenarios, the low-volume scenarios could have better VSL control performance, which might be due to severe traffic congestion. The results of VSL control only under different traffic conditions are consistent with the findings of previous studies [7, 46].

Table 4-3 Effects of VSL only

Measurement	**Volume**	**VSL Compliance Rate**		
		30%	**60%**	**100%**
Change of $TTC_{brake\%}$	Low	-11.5%	-23.1%	-29.5%
	High	-0.3%	-1.3%	-6.3%
Change of *TTT*	Low	+1.9%	+13.8%	+26.9%
	High	+3.9%	+3.8%	+3.5%

Figure 4.6 illustrates the $TTC_{brake\%}$ curves for non-VSL scenarios and VSL scenarios under three compliance rates. It was further confirmed that the VSL strategy could successfully reduce the $TTC_{brake\%}$ value during almost all the VSL-implemented periods. For the scenarios with low volumes, the VSL control could consistently provide lower rear-end crash risk compared with the

scenario without any control. On the other hand, the scenario with high volume could consistently improve the safety performance when the compliance rate was 100%. However, the VSL control could not provide stable performance over time for the high volume when the compliance rate was 30% and 60%, although it could generally reduce the total rear-end crash risk.



(a) Low volume **(b) High volume**

Figure 4.6 - $\mathbf{TTC_{brake\%}}$ for the study area under different VSL compliance rates

Figure 4.7 shows the reduction of $TTC_{brake\%}$ by each detector when compliance rate was 100% for low volume, which showed the largest safety improvement. It was indicated that the VSL could consistently reduce the rear-end crash risk for the locations (Detectors #2, #3, #4, and #5) at the upstream of the crash location except for the location of Detector #6, which is quite far from the crash spot. In addition, the effect of the VSL control is not significant (i.e., the reduction is close to 0) for the location (Detector #1) at the downstream of the crash location.

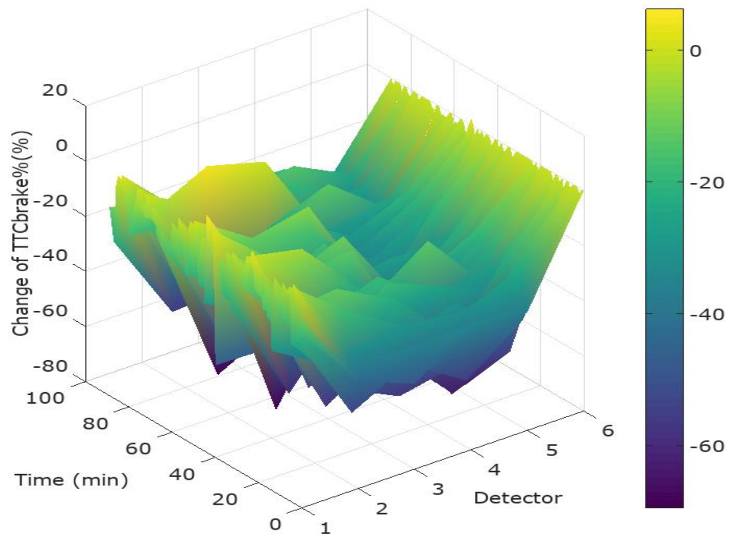


Figure 4.7 - Reduction of $TTC_{brake\%}$ with 100% VSL compliance rate for low volume

Moreover, Table 4-3 also suggests that travel time is increased if the VSL control is implemented. The basic idea of a VSL control is to reduce vehicles' speeds to avoid traffic crashes proactively. Hence, efficiency is sacrificed for safety because of the reduction in average speeds [8]. For the low-volume scenarios, the TTT increased more as the VSL compliance rate increased, and the TTT increased by 26.9% when the compliance rate was 100%. Meanwhile, the TTT increased by around 4 for the high-volume scenarios with different compliance rates**.** It is worth mentioning that the 26.9% increase in travel time is still acceptable because the VSL control could reduce the rear-end crash risk by 29.5%; additional crashes could cause more delay.

4.1.6 Effects of Connected Vehicles (CV Only)

Table 4-4 shows the change in rear-end crash risk and *TTT* by the CV control compared with the base condition without any control. It is suggested that the CV control could both decrease rear-end crash risk and increase traffic efficiency. Under fog conditions, a rear-end crash is prone to occur since drivers could not clearly see the situation in front of them with the reduced visibility. With the CV control, vehicles could communicate with each other and drivers could be informed of dangerous situations. Thus, the adverse effect of fog could be efficiently mitigated by the CV control. CV's effects are more significant in low-volume scenarios (34.6% risk reduction) when drivers are less likely to observe lead vehicles with large gaps. Meanwhile, CV is prone to have smaller gaps because drivers could be more confident about their driving due to the information provided by CV technologies. Thus, smaller *TTT*s were observed under the CV environment, which illustrates that the CV could effectively improve traffic efficiency, especially under high-volume conditions (64.3% TTT reduction).

Table 4-4 Effects of CV only

Measurement	Low Volume	High Volume

Change of $TTC_{brake\%}$	-34.6%	-2.5%
Change of *TTT*	-3.8%	-64.3%

4.1.7 Effects of Variable Speed Limit and Connected Vehicle (VSL & CV)

Table 4-5 provides the comparison of the effects of VSL only with 100% compliance rate, CV only, and VSL & CV. Negative values of the change of $TTC_{brake\%}$ or the change of TTT indicate reduced crash risks or improved traffic efficiency. As discussed in the previous two subsections, both VSL-only and CV-only control strategies could efficiently reduce the rear-end crash risk for both low- and high-volume conditions. In addition, the better performance of the VSL control could be found in the CV environment, indicating the advanced characteristics of the V2I and V2V control systems. When a safe speed limit is determined by the proposed VSL control algorithm, the information could be sent to all the CVs at the segment immediately, and all vehicles would follow the suggested speed. Compared to drivers without any control, the CVs would follow the proposed safe speed homogeneously. In addition, CV could diminish the increase in travel time caused by the VSL strategy, especially for high-volume conditions. The results of the combined VSL and CV control strategy are in line with other similar investigations [38, 60].

Table 4-5 Effects of VSL/CV under different control situations

	Low Volume			High Volume		
	VSL	CV	VSL & CV	VSL	CV	VSL & CV
Change of $TTC_{brake\%}$	-29.4%	-34.6%	-48.7%	-6.3%	-2.5%	-6.6%
Change of *TTT*	+26.9%	-3.8%	+22.8%	+3.5%	-64.3%	-55.2%

In order to further confirm the effects of VSL and CV, $TTC_{brake\%}$ of each detector is plotted in Figure 4.8. For the low-volume conditions, the CV-only and VSL & CV control strategies could consistently reduce rear-end crash risk for all the locations, while the VSL-only control strategy could significantly improve the safety performance for the locations at the upstream of the crash spot except for Detector #6. For the high-volume conditions, the effects of the VSL-only and CV-only control strategies could not be clearly identified from the figures. However, it is clearly indicated that the combination of VSL and CV could reduce the rear-end crash risk for the locations at the upstream of and close to the crash spot (Detectors #2, #3, and #4), where higher crash risk and more severe congestion are expected.

Figure 4.8 - $TTC_{brake\%}$ of each detector for VSL only, CV only, and VSL & CV

5 Conclusion

9. Conclusion for Connected-Vehicle Crash Warning System

In Chapter 3, we investigated the effects of connected-vehicle (CV) crash warning systems (CWS) on drivers' rear-end crash-avoidance performance when the lead vehicle made an emergency brake under fog conditions. Response time (i.e., perception response time and brake reaction time), minimum modified time-to-collision, and maximum brake pedal pressures are important variables indicating drivers' safety conditions. The experiment results indicated the positive effects of a CWS on safety. It was found that the warning system can significantly reduce drivers' brake response time and increase minimum modified time-to-collision. Nevertheless, no significant additional effect of audio warning could be found. Additionally, the decrease in visibility distance could increase the crash risk, and older drivers are more vulnerable road users under fog conditions. No significant gender effect could be identified in this study.

This study used a simulator-based experiment to examine the influence of CWS during fog. Results showed that drivers tend to adjust their braking behavior with the presence of CWS. Earlier responses and a smoother braking process were observed under the CV warning environment.

Overall, greater safety benefits and better driving performance could be achieved by providing CWS under a CV environment during fog. Because the vehicle-to-vehicle (V2V) and vehicle-to-interface (V2I) communications are not affected by the reduced visibility, more accurate information could be provided to drivers. Thus, the effectiveness of the CWS could be enhanced by CV technologies. The findings of this study are relevant to the incorporation of warning and V2V and V2I applications of CV during inclement weather conditions. Such applications could help drivers avoid rear-end crashes under reduced visibility conditions.

10. Connected Vehicle and Variable Speed Limit Controls under Reduced Visibility Conditions

This study aimed to reduce the rear-end crash risks near a freeway bottleneck under fog conditions by integrating variable speed limit (VSL) and CV control techniques. Based on the car-following analysis, a VSL control strategy was developed with consideration of the different relationships between the gap and the visibility distance suggested by Wu et al. [3]. Then, the developed VSL control strategy was combined with the CV control with a feedback control framework. The VSL control algorithm was fulfilled by the VISSIM-COM interface, and an Intelligent Driver Model (IDM) that was coded by C++ was included in the CV-related VISSIM scenarios to represent the change of driver behavior under a CV environment. The VISSIM model that was employed in this study was carefully calibrated and validated based on field traffic data and weather data during a foggy period on February 2, 2016 (6:15 a.m. – 8:15 a.m.). A 10-mile section of I-4 westbound that has experienced a severe fog-related crash was coded in the micro-simulation software VISSIM. A total of 12 scenarios were conducted to investigate the effects of VSL control only with different drivers' compliance rates, CV control only, and integrated VSL and CV control under two different traffic volume conditions. All the results were quantified as change of TTC at braking ($TTC_{brake\%}$) and change of total travel time (TTT) across ten runs. Based on the simulation results, the following conclusions can be made:

- Compared with the vehicles without any control, the proposed VSL control strategy could effectively reduce the rear-end crash risk under fog conditions. The safety performance of VSL is better with a higher driver compliance rate. When the compliance rate is 100%, the rear-end crash risk could reduce by 29.5% and 6.3% for low- and high-volume conditions, respectively. However, because the idea of VSL control is to enhance safety by suggesting a lower speed, the VSL control could reduce traffic efficiency at an acceptable level.
- The results demonstrate that CV could also improve traffic safety and traffic efficiency.
- Implementing VSL in a CV environment (VSL & CV) could further enhance safety, while CV could diminish the increase in travel time caused by VSL control.
- Crash risk migration was not observed during the simulation when the control strategy was implemented, suggesting that traffic safety could be improved consistently.

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Appendix A: Protocol and Study Materials

Evaluating Managed Lane and Fog Systems Conditions Using Driving Simulation

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1. 1. PROTOCOL TITLE

Evaluating Managed Lane and Fog Systems Conditions Using Driving Simulation

2. PRINCIPAL INVESTIGATOR

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3. OBJECTIVE

There are two main objectives for this driving simulator experiment. The first is to determine driver behavior in varying fog conditions and explore the impacts of different fog warning systems on driver behavior. The second is to study driver behavior while driving from general purpose lane to managed lane. To do this, participants will run through different scenarios on a NADS MiniSim driving simulator provided for the research. Variables of interest for the experiment will also be collected from the participants, which will be observed with the results of the simulations to see if there is any correlation with these variables and the results from the scenarios. These variables will be collected confidential and include the participant's age, gender, driving experience and frequency, highest education level, accomplished income level, or zip code, and whether they have been in an accident in the last 3 years. Questions will also be given to the participants in written form before, during, and after the experiment in order to collect additional information that may provide an impact in the results. Feedback will also be collected from the participants at the end of the simulation which will be used to make improvements to future simulation research projects. Further, a questionnaire survey will be also conducted to investigate users' preference on HUD design under fog condition.

Source: Mini Sim Driving Simulator
(http://sonify.psych.gatech.edu/research/driving/index.html) (4)

Questions asked prior to the simulation testing involve determining the participants driving history and experience, as well as familiarity in fog conditions and managed lane, as well as variable collection. These questions also allow us to get a better understanding of individuals driving habits and whether they will experience any sort of motion sickness during the testing. At the end of the entire simulation test, subjects will again be asked if they are feeling well enough to leave and feedback will be collected from the participant on what they thought of the simulation experiment. By using this feedback, we have the opportunity to improve future simulation studies. (Samples of these questions that will be asked can be found on the attached questionnaire.)

Once the simulations have been completed and the required data has been collected, we will then analyze the results to see how people react in fog and warning systems, as well as managed lane. From our research, we hope to find ways to improve the safety of our roadways by determining potential benefits from the tested environments.

4. BACKGROUND

Studying driving behavior in a real world scenario can be extremely challenging and dangerous, especially when these situations involve adverse conditions, such as fog. Due to unpredictability, it is hard to create fixed or constant environmental factors along the physical roadways. Interference from other drivers can also complicate data and also pose potential safety hazards when trying to conduct studies with volunteers. Simulations allow us to test specific scenarios under user specific conditions, allowing for more control over the environment and consistency between each participants tests. Using simulation software also allows a cheaper alternative to testing driving behaviors compared to bigger more advanced systems such as Virginia Tech's "Smart Road." Although the simulation scenario is not as realistic as a 'real world' setting, we can validate the data in many different ways, one of which, stated by Dr. Kathy Broughton, Dr. Fred Switzer, and Dr. Dan Scott in their "Car Following Decisions" paper, would be to simply compare it to results from 'real world' studies and see if the trends are comparable (1-2). This is an absolute possibility for this research, as a sensor will be placed at the location the fog scenarios are based off of. Ultimately it was determined from the investigation that driving simulation studies were much safer and more economic than a real world setting.

Currently, there have been many research and study topics involving the analysis of driver behavior in fog conditions using driving simulation. However, many focus on simply how varying fog levels compare to collision, driving behavior, or sight distance. For this study, we will be focusing on whether the presence of a warning system effects an individual's driving behavior in fog conditions, and in what way it impacts this behavior. Validation in this regard will be fairly simple as well thanks in part to the previous fog simulation studies. Again, many of these past studies have focused on purely driving behavior, and many of which drew similar conclusions and results based on their studies. It was found that there is much consistency in driving behavior (acceleration or deceleration in fog, braking, speed, ect.) in fog conditions (3), meaning that it could be possible to validate the results based on other simulation findings if the data is consistent.

Besides, the research team will investigate the effectiveness of warning strategies on low visibility conditions utilizing driving simulator. Various low visibility warning systems will be tested for different combinations of scenarios to assistant drivers' decisions or avoid certain type of crashes. Based on the tested results of driver behaviors, we can examine which warning types are the most safety effective among the various types such as messages (e.g., sentence, pictogram, etc.), sound, and vibration. It is expected that appropriate warning systems can be suggested to enhance safety in fog condition based on our driving simulator experiment.

Besides the fog conditions, the managed lane is also studied in our experiment. Managed Lanes are designated lanes where the flow of traffic is managed by limiting vehicle eligibility, restricting facility access, or variable price tolls. The managed lanes have emerged as an effective dynamic traffic management strategy. In recent years, several major cities in the United States have introduced managed lane systems such as ETLs (Express Toll Lanes), HOT (High-Occupancy Toll) lanes, or HOV (High Occupancy Vehicle) lanes.

In order to efficiently and safely operate the managed lane system, it is necessary to determine the safe length and location of weave access zones nearby on- or off- ramps. Although many managed lanes have been built and various safe length has been recommended (4-5), most of studies were based on microsimulation. In our driving simulator experiment, we aim to test drivers' lane changing behavior and investigate whether the length is sufficient for the drivers to merge into or out from the managed lane. Drivers require enough time (distance) to decide to use (leave) the managed lane. This decision-making process should take more time compared to general lane changing, merging or diverging, since they need to reasonably think if they have a willingness to pay the current toll rate in improve mobility (e.g., reduced travel time). Thus, there are two major cases we need to consider: fist, a distance from an upstream managed lane exit to the next downstream off-ramp; second, a minimum distance from an upstream on-ramp to the next downstream managed lane entrance.

5. SETTING OF RESEARCH

The simulation study will be conducted at the University of Central Florida, in one of our available offices in Engineering building II. The office itself is large enough to accommodate the testing equipment and personnel, and is easily accessible by the research assistants. Since the research location is conducted within the UCF engineering building, many accommodations and equipment are readily available in case of any issue. Restrooms and water fountains are accessible to participants and personnel, and first-aid kits, fire extinguishers, and so on are also ready to use.

6. RESOURCES AVAILABLE TO CONDUCT HUMAN RESEARCH

Since we plan on recruiting many of the participants for this study through friends, family, and the University itself, many recruitment options are available to us. Friends, family, and even possibly campus faculty can be easily contacted and requested for participation either in person or by other means of communication. However, recruiting students for the study will require a bit more work to accomplish. The current plan is to advertise the study by word of mouth in classrooms, clubs, and around campus to recruit potential volunteers for the short study.

Overall, the simulation study should only take around one hour to complete, making time commitment not a huge problem. This hour block includes pre-simulation procedures, such as going over the disclaimer and allowing the participant time to practice to become more acquainted with the simulator. Three questionnaires will be given to the participants throughout the study. One is before driving the simulator, and two are after the experiment. Following these preliminary procedures, each subject will then run through 7 scenarios chosen at a random order from a pool of created scenarios. The scenarios chosen will vary between the managed lane and fog related scenarios. Assuming each scenario lasts 4-6 minutes, there should be plenty of time to familiarize the participant, run the tests, and even allow some time in between tests for the participant to rest if he or she needs it.

A majority of the research group involved in the research have a few years of transportation safety research experience, a few already obtained PhD's in the field. We are also working with other universities in the country. These include the University of Massachusetts Amherst and the University of Puerto Rico who have current experience in simulation research. The other universities will have no access to the data that we will collect. The only collaboration we will have and have had with these universities is guidance with simulation research, since they have more experience in the field. Furthermore, we will only share our results and findings with them in order to expand this research further. They are not involved in the data or experiments.

As previously stated, the simulation will be conducted in a private office inside Engineering Building II on UCF campus. Access to the room is approved, and only a select few research staff have access to the room and simulator. Amenities, such as water fountains and restrooms are readily available, as well as seating if someone needed to rest. While the simulation is being conducted, participants will be with at least one staff member at all times to monitor them and walk them through the procedure.

7. STUDY DESIGN

7a) Recruitment

For this experiment, a maximum of 126 subjects will be needed to run the simulation and be tested. The subjects will ideally range from ages 18 to 65, and each will be a Florida resident. Since most of the variables of interested in this study are based on the participants' demographics, a nice even distribution will need to be met to assure unbiased results. To meet this, we will recruit a variety of subjects with varying age, gender, education, ethnicities, and backgrounds. Participants will run the simulations through voluntary means, and will be recruited through UCF clubs and classes, friends or relatives, and possibly other local students who are interested in the research. No matter how they are recruited, each participant is expected to run through the scenarios presented in the MiniSim as if they were, or as close as possible to, driving in a real life scenario.

Participants will be recruited during the months of February, March, and possibly April. The family and friends of the researchers be recruited by word of mouth or by e-mail. Likewise, faculty and staff will also be recruited by word of mouth or by e-mail. A description will be given to explain the basis of the research and will be sent out through these e-mails.

Identifying potential participants will not be a difficult task for this research because the only requirements are as follows: The participant must be in the age range of 18 to late 60's, must have a driver's license, and must not have a history of motion sickness. Being in a college environment, it should be possible to find many potential participants. As stated previously, 54 subjects will be needed to complete this research study.

7b) Compensation

Since this experiment will only last one hour in total and it is being ran strictly through voluntary participants, no compensation is planned on being offered.

7c) Inclusion and Exclusion Criteria

In order to be eligible for this research experiment, participants must fit within a predefined demographic determined by the research group. The demographic of interest includes both male and female Florida residents ages 18 to 65. The participants must have a valid driver's license and have no history of extreme motion sickness or other medical conditions that can be caused by disorientation such as seizures or strokes. Subjects must also be physically capable of concentrating at a computer screen for at least half one hour without having any complications.

Each person who partakes in the simulation testing will have general information about themselves questioned and or recorded. These include age, gender, ethnicity, driving experience and history, approximate income, and a few other general variables that could prove to be significant in the final analysis. Assuming the participant meets the required criteria and performs the simulation, additional variables and information will be gathered from the participant including data from their scenario performance and info on the driver's reaction based on their answers to the post simulation questions. The data that we are most interested in for this experiment is primarily the driving behavior, including speed, acceleration or deceleration rates, brake usage, lane changing, and vehicle distancing just to name a few. With the addition of the questionnaire we can also gain information in regards to how the participant reacted to the given scenarios. Information such as; were the sign(s) encountered easy to read or understand, how confusing the scenario was, or even how they reacted to a specific event can provide valuable research information in terms of driver reactions.

Again, 126 participants are expected to be needed for the study; the results from each subject are expected to be used. The only situation where data results will be ignored or not used is if a situation occurs that results in an early withdraw of the participant or an error occurred during the simulation. Since the experiment requires the participants to have a driver license and must be at least 18 years or older, no children or teenagers will be considered for this research.

7d) Study Endpoints

N/A

7e) Study Timelines

The participants are expected to come to do the experiment twice, at the very most, 30 minutes for each time. This includes the explanation of what will be needed of them during the study, the scenarios the subject will be tested on, and breaks in between scenarios, as needed. It is estimated that testing will take 3 to 4 months. The primary analyses should be completed by May 2017.

7f) Procedure

The overall procedure for running the simulation should not take more than one hour for each participant, and each run will aim to be as consistent as possible. Before the simulation is started, each participant will be given a consent form that goes over what is expected of them and any possible health advisories. This consent form must be read and sign by any participant before any testing can begin so each participant knows what to expect. Once this is done, the subject will be given preliminary questions in written form, including questions on the variables of interest (age, gender, etc.), and then will be given a test simulation to get them more acquainted and comfortable with the hardware. This portion of the procedure should take approximately 10 minutes where ideally the participant gets 5 minutes of test driving in the simulator.

Following this initial practice, the participant will be given short rest if needed and then the actual study scenarios will be provided. Prior to starting the group of scenarios, the participant will be reminded of what their task is in the simulation. Between each scenario group, the participant will also be given the option to take a rest if they are feeling motion sick or ill, and if they are unable to continue the test will be concluded. After driving the simulator, the participant will be questioned in regards to the scenarios they just ran and their preference of head-up display design for fog conditions. Attached is a copy of each questionnaire used.

Since this simulation study is looking at both fog warning systems and managed lane conditions, the scenarios that the subjects will run involve completely different conditions. To keep things more in order and consistent, the groups of scenarios will each be based on one study. For the first group, both a freeway and arterial road will be generated and along them will contain a random fog and sign condition. In order to create a valid experiment, a pool of many different scenarios with varying conditions will be created, but only a few will be used randomly on each participant. The same applies for the managed lane as multiple conditions could be present and needs to be tested.

Ideally seven random scenarios will be chosen for both the fog and managed lane simulations, each taking around 4 to 6 minutes. After all this simulation data is collected, analysis will begin to determine correlation between driving conditions and participant data.

There are four recording devices that are used by this simulator. One device is pointed directly at the participant's feet and will record only their feet. One is directed towards their face and another towards their hands. The last recording device will be located behind the participant, recording the monitors and where they direct the simulated vehicle. It is necessary to note that the researchers will be the only people that will access these videos and they will be deleted immediately after the necessary data is collected. The videos will be stored in a locked, safe place. The data collected from these videos include, but are not limited to, eye movements, gas and brake pedal usage, and head movements. There is very minimal risk when using the MiniSim. The only risk the subjects have in using the simulator is motion sickness. In this case, the subject would be provided water and a cool place to sit. The motion sickness will be monitored by the research assistants who will watch for signs of uneasiness.

Data collected during the experiment range from how the subject uses there pedals to how often they switch lanes to swerving. Data will also be collected using the questionnaires. This data includes age, gender, years of driving experience, years of driving experience in Florida, how often a person uses toll roads or roads susceptible to fog, occupation, range of income, highest level of education, how realistic the person thought the scenarios were, etc.

For the fog related scenarios, the participant will drive through arterial lanes with varying fog and warning system conditions. These scenarios will be based in Paynes Prairie, Gainesville; a location that has seen severe crashes in the past due to visibility issues. By basing our study on this location, we gain the added benefit of using data collected from the actual site to compare and validate the simulator results. As previously stated, multiple scenarios will be made for different situations including fog density and warning system presence. Normally each scenario will begin under clear or slight fog conditions and as the driver proceeds down the courses, the set conditions will begin to change. From this pool of scenarios, 3 scenarios will be randomly selected for each participant to run.

The managed lane simulation will be based on the managed lane on Interstate Road 95 in Miami, Florida. In order to merge into managed lane, drivers need to change multiple lanes. Thus, it could be extremely dangerous if the length for drivers to change lanes from ramp to managed lane or from managed lane to ramp is not enough. There are two major cases we need to consider: first, a distance from an upstream managed lane exit to the next downstream off-ramp; second, a minimum distance from an upstream on-ramp to the next downstream managed lane entry. Drivers require sufficient time to decide to use (or leave) the managed lane. This decision making process takes more time compared to general lane changing, merging or diverging, as they need to reasonably think if they have a willingness to pay the current toll rate to improve mobility (e.g., reduced travel time).

7g) Data Specimen Management

N/A

7h) Provisions to Monitor

N/A

7i) Withdrawal

If participants show continuous or extreme signs of motion sickness, he or she will be withdrawn from the simulation test. Once withdrawn, the participant will be given a place to rest and water until they feel well enough to leave.

In a situation where a participant was withdrawn from a test, the data collected will most likely be invalidated and will not be used. However, if the participant completes a specific scenario prior to the issues causing the withdrawal to occur, then the data for those scenarios might still be usable.

8. RISKS

The main risk that is encountered while driving in the simulation is motion sickness, or any other form of motion related ailments. If a subject begins to feel any uneasiness or needs a break, they will be free to do so. Once out of the simulator, the sickness should subside momentarily. At the end of the test, subject will also be questioned to give them time to relax and will be offered a place to rest if they need some time before they leave. Also, were any serious problem occur, a researcher will be with the subject at all times so participants should never be along for long periods of time.

9. POTENTIAL BENEFITS

Overall there is no real direct benefit towards participants in this study other than compensation or learning something about the transportation engineering field and simulation research. The participant will also be contributing to research for safer and more efficient roadways.

10. PROVISIONS TO PROTECT PRIVACY OF PARTICIPANT

The simulation tests will be conducted behind closed doors with only the research assistants and participant present. The data collected from the subject will be completely confidential, where no information collected from the participant will be related to a name or identity. If subjects are not comfortable answering a question, such as income or crash history, a value range will be provided to choose from or the participant has the right to not answer. The data collected will be strictly used for academic purposes and will only be accessible to those involved in the research group.

11. PROVISIONS TO MAINTAIN CONFIDENTIALITY

In order to maintain confidentiality of the data, as well as the participants, all data collected will be kept secure where only research staff will be able to access and look at it. Subject names will also not be used, recorded, or related to the data collected from the participants in order to assist in creating anonymous data. The data is also going to be restricted to limited use, not only by who can access it but also where it can be accessed. The data will be stored for at least five years after the research study has been completed, per UCF IRB Policies and Procedures.

12. MEDICAL CARE AND COMPENSATION FOR INJURY

N/A

13. COSTS TO PARTICIPANTS

Participants may incur a cost for parking, if this occurs, they will be reimbursed.

14. CONSENT PROCESS

All consent will be taken care of at the very start of the study, prior to any simulation testing on the participant. Each participant will be given an informed consent form that they are to go over before any testing can begin. While the participant does this, the available staff at the time will go over the form with them, ideally in the first 10 minutes, covering the most important parts of the document and check with the participant to ensure that they understand what is being discussed. This means that before any testing has begun, the participant will have been given a verbal form of consent for both what is expected of the simulation as well as understanding. The potential participants will be asked if they have had a seizure or if they have a history of seizures. They will be excluded from partaking in the study if they answer “yes” to this question. Also, since the participant if free to withdraw from the simulation at any time, a person’s willingness to continue shows adequate ongoing consent.

Since all the participants expected to take part in this experiment are Florida residents, we can assume that practically all of the participants will have English as a primary language or at least have a firm grasp the language. This will be the only language spoken during the study and we will not be able to recruit participants that do not know English.

15. CONSENT DOCUMENTATION

A written consent form will be provided prior to any testing, and will be gone over by the tester to ensure the participant understands everything. Before the simulation is started, each participant will be given a consent form that goes over what is expected of them and any possible health advisories. This consent form must be read by any participant before any testing can begin so each participant knows what to expect. The assistant conducting the research will also be available to answer any questions the participant may have and go over the consent form with them. Once this is done, the participant will be given preliminary questions, including questions on the variables of interest (age, gender, etc.).

16. VULNERABLE POPULATIONS

N/A

17. DRUGS AND DEVICES

N/A

18. MULTI-SITE HUMAN RESEARCH

N/A

19. SHARING RESULTS WITH PARTICIPANTS

N/A

SUMMARY

Through observation of the results of these simulation scenarios, we hope to use the findings to determine more efficient ways to use warning systems for adverse weather conditions, as well as improve efficiencies at managed lane. The work done and data collected also provides a base for other research projects and studies to read the data or do further testing on the results. As far as fog research, these studies can include closer analysis on the type of warning systems used. These managed lane studies will comprise of determining safe length of location of weave access zones nearby on- or off- ramps.

Again, one of the biggest issues with simulation studies is validation of the simulation environment to accurately reflect real world data. Luckily, this will not be too big of an issue due to having access to traffic data collected from the sites of interest.

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Appendix B: Simulation Questionnaire

SIMULATOR QUESTIONNAIRE

Before the Experiment

1. How old are you?

____

2. What is your ZIP code (9-digit, on your driver license)?

					--				

3. What is your highest level of education?
   a. Less than high school diploma
   b. High school diploma
   c. Associate bachelors' degree
   d. Bachelor's degree
   e. Advanced degree or professional degree

4. Are you a professional driver / Does your job involve driving?
   a. Yes
   b. No

5. How long have you been driving a car?

____

6. How many years have you been driving in Florida?

____

7. Where did you learn how to drive?

   a. In Florida
   b. Outside Florida, but in United States
   c. Outside United States

8. What vehicle do you usually drive?
   a. Passenger Car
   b. Light Truck or Van
   c. Motorcycle
   d. Recreational Vehicle (RV)
   e. Other. If so, what is the vehicle type: _____________

9. How often do you typically drive?
   a. 1-5 trips per week
   b. 1-2 trips per day
   c. 3-5 trips per day
   d. 5+ trips per day

If never, please explain:

10. Have you ever driven in any fog conditions in the past year?
    a. Yes
    b. No

11. Have you ever driven a car with Head-up display (HUD)?
    a. Yes
    b. No

12. Have you been involved in any vehicular crash in the last 5 years?
    a. Yes
    b. No

    If so, what was the crash type (e.g. sideswipe, rear-end, head-on, etc.)?

    How many cars were involved?

    Where did the crash occur (e.g. intersection, highway, toll plaza, etc.)?

Did you receive a citation when you were involved in the crash?

SIMULATOR QUESTIONNAIRE

After the Experiment

1. How do you feel? Are you capable of leaving or need some time to rest?

2. Do you have any suggestions or feedback on how to improve the simulation or have any complaints in regards to the scenarios you ran?

3. Do you think the scenarios were logical and realistic to an actual life situation?

4. What did you like and dislike about the simulation?

5. Under the connected vehicle environment, how helpful was the “Slow Vehicle Ahead” warning in the Head-up Display?

1	2	3	4	5
Not at all helpful	Not very helpful	Somewhat helpful	Helpful	Very helpful

6. Under the connected vehicle environment, how helpful was the warning sounds with the Head-up Display?

1	2	3	4	5
Not at all helpful	Not very helpful	Somewhat helpful	Helpful	Very helpful